Snow and glaciers

Vatnajokull, Iceland

Today's goals

- Understanding of different snow & ice impacts on runoff
- Knowledge on main snow & ice model concepts
- Impact of climate change on snow & ice processes

Snow, glaciers and catchment hydrology

In many (mountainous) catchments, snow processes dominate the hydrological response.

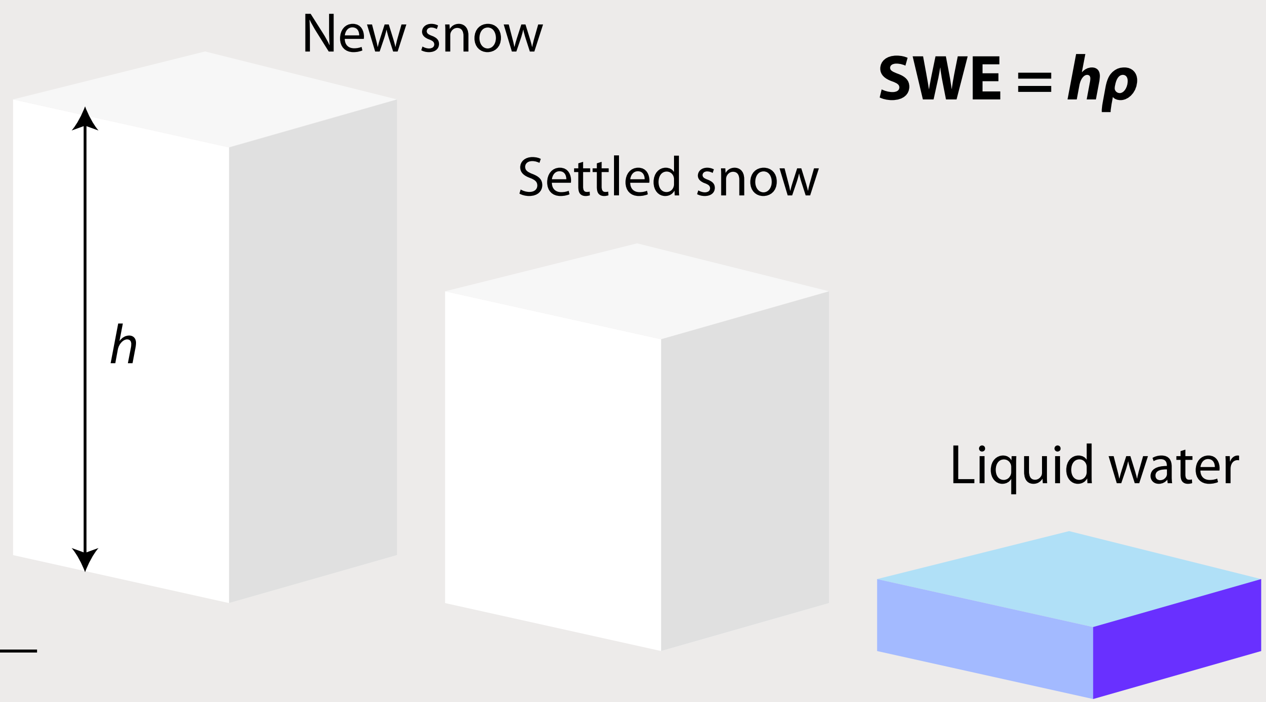
Snow is “passive” storage; it can be present in the catchment without affecting streamfow if temperatures are low enough.

Snowmelt can dominate the seasonal discharge patterns, distributing water availability over wet and dry seasons.

Vatnajokull, Iceland

Snow depth and snow water equivalent (SWE)

$$\mathbf{SWE} = \boldsymbol{h\rho}$$



Density (ρ, in kg/m^3)

New snow	50-70
Damp new snow	100-200
Settled snow	200-300
Firn	400-830
Glacier ice	830-917
Liquid water	1000

Snow depth can be measured directly

but: SWE needed for water balance-based modeling

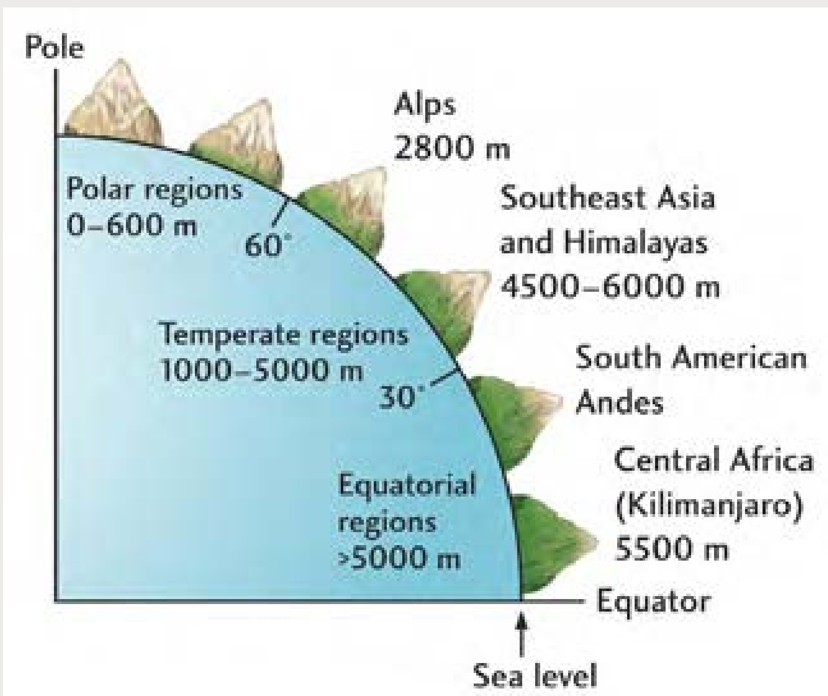
Conversion requires snow density, which depends on snow structure and age

Paterson, W.S.B. 1994. The Physics of Glaciers.

Snow line

Vatnajokull, Iceland (64N) snow line 700-1100 m

The climatic **snow line** is the altitude above which snow covers the ground throughout the year. It varies strongly with latitude, and depends also on climate.



Variations in the climatic and seasonal snow line are related to the atmospheric **lapse rate**, which relates temperature and height. In a standard atmosphere, air temperature decreases **6.5 K** every 1000 m.

Cotopaxi, Ecuador, snow line 5000 m

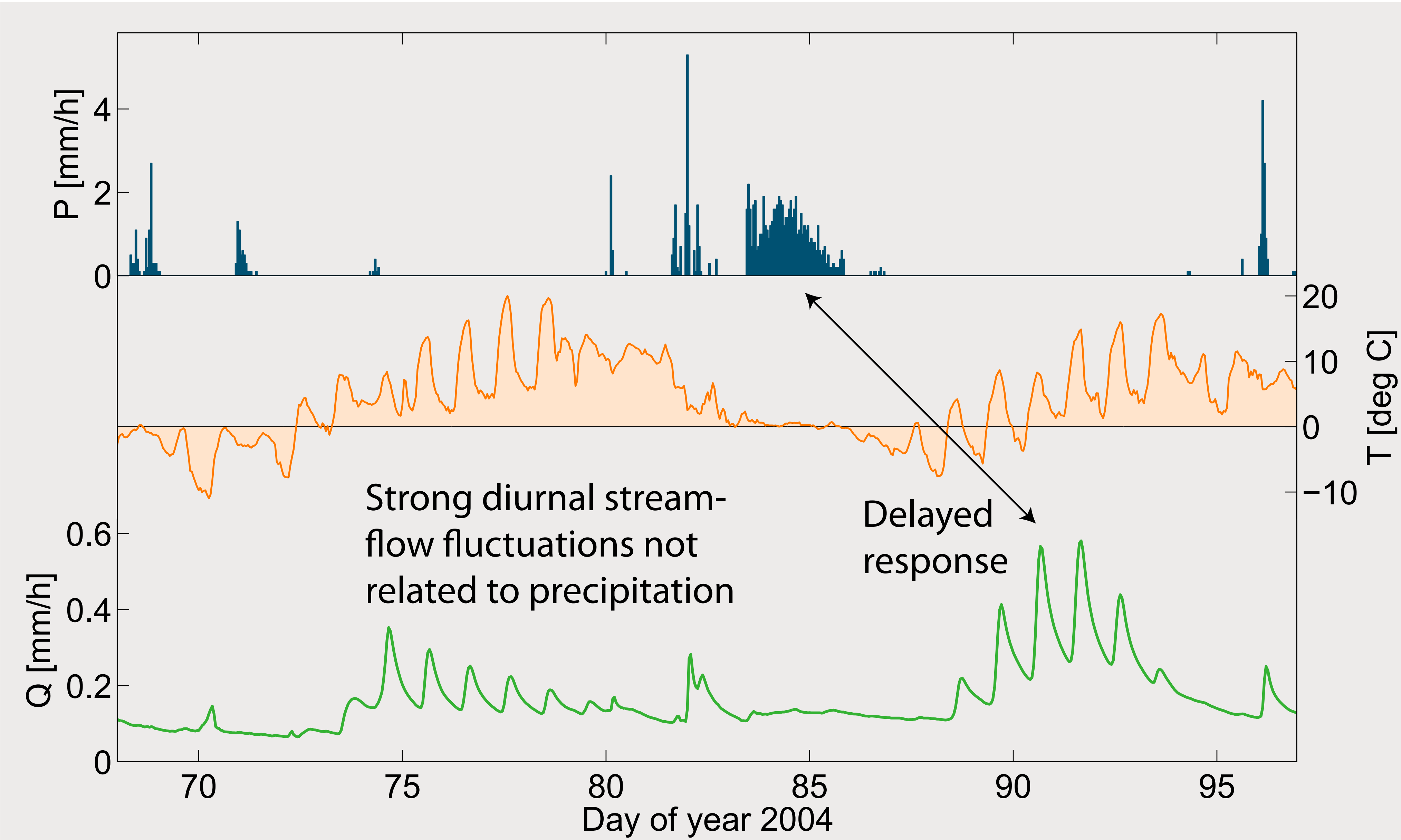
Snow parameters derived from time lapse images

Time-lapse camera

Snow processes can be easily observed by low-cost time-lapse cameras. Multiple cameras were installed in the Swiss Rietholzbach catchment during winter 2013/2014 with the aim to identify snowmelt parameters.

http://www.brinno.com/html/TLC100.html

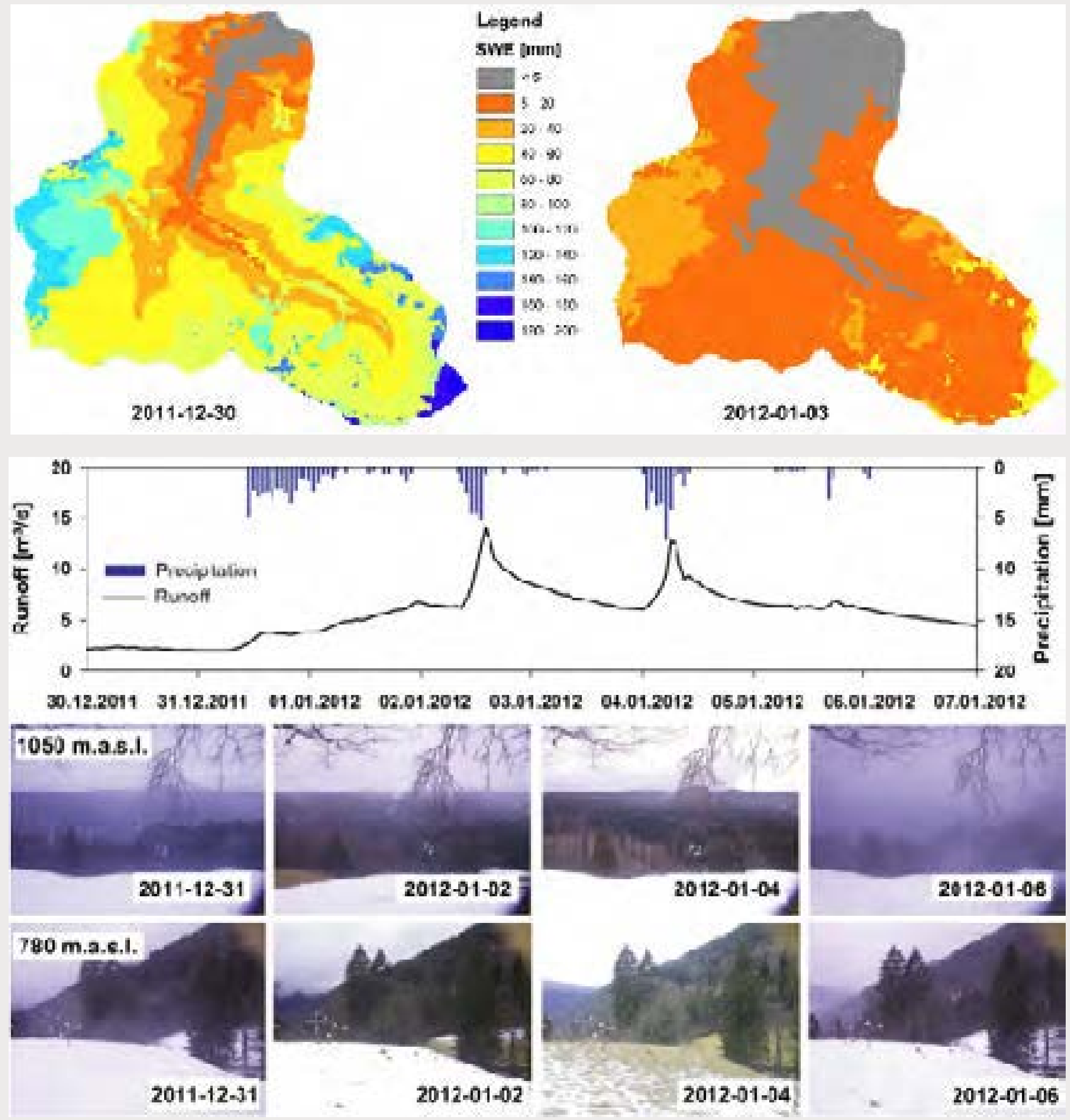
Example: Rietholzbach Spring 2004



Seneviratne et al., 2012. Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event. *Water Resour. Res.* **48**

2012 Rain on snow event, Black Forest (Germany)

Liquid precipitation on snow can result in strong melt peaks. These events are called **rain on snow** (ROS) events. An ROS event on 2 January 2012 resulted in a flood peak with recurrence times exceeding 2 years due to additional runoff water from snowmelt.



Brugga catchment example

Precipitation	44 mm
Pre-event SWE	56 mm
Post-event SWE	13 mm
Potential runoff	87 mm
Observed runoff	83 mm

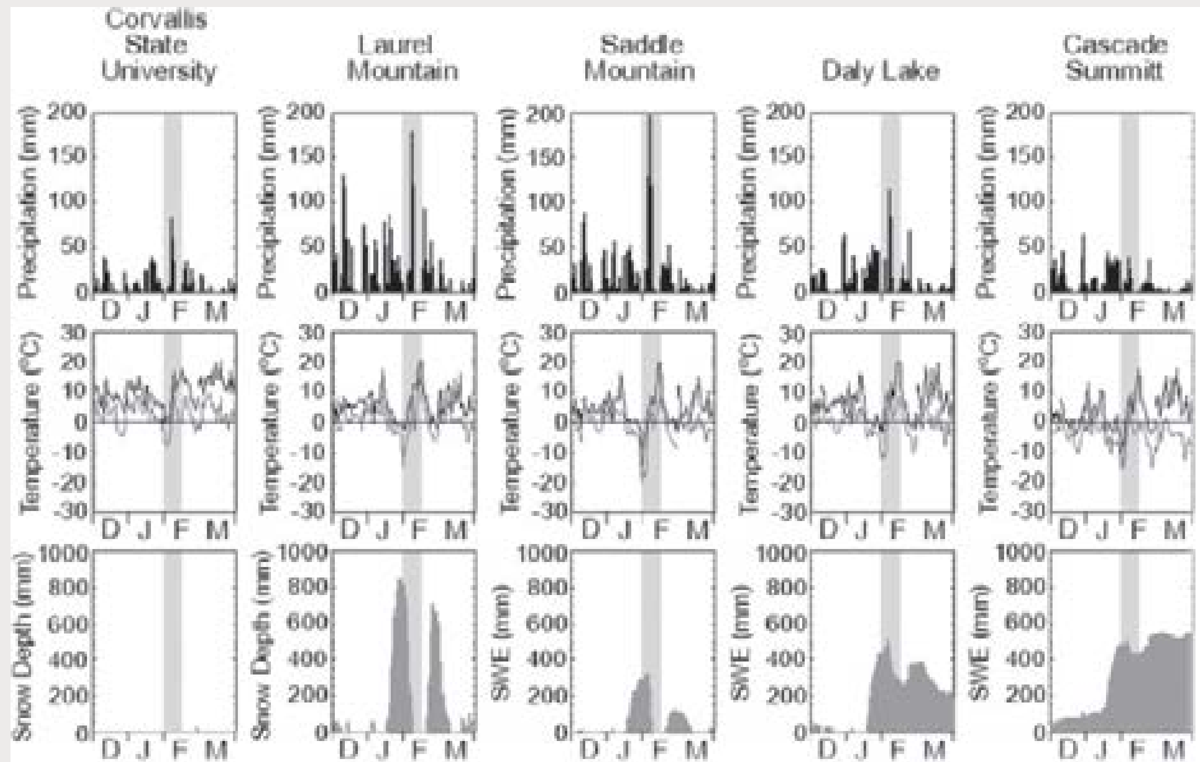
Garvelmann et al., 2013. From observation to the quantification of snow processes with a time-lapse camera network. *Hydrol. Earth Syst. Sci.* **17**

1996 Pacific Northwest floods (Willamette valley)

A warm and very wet pacific storm hit the Oregon Cascades in February 1996, thereby providing the energy for rapid melting of a thick snowpack. This locally doubled the water available for runoff. Melting was strong over open land, whereas forest cover limited efficient energy exchange between the snowpack and the atmosphere.

Daly lake example

Elevation	1100 m
Precipitation	279 mm
SWE loss	211 mm
Potential runoff	490 mm
Snowmelt contribution	48%



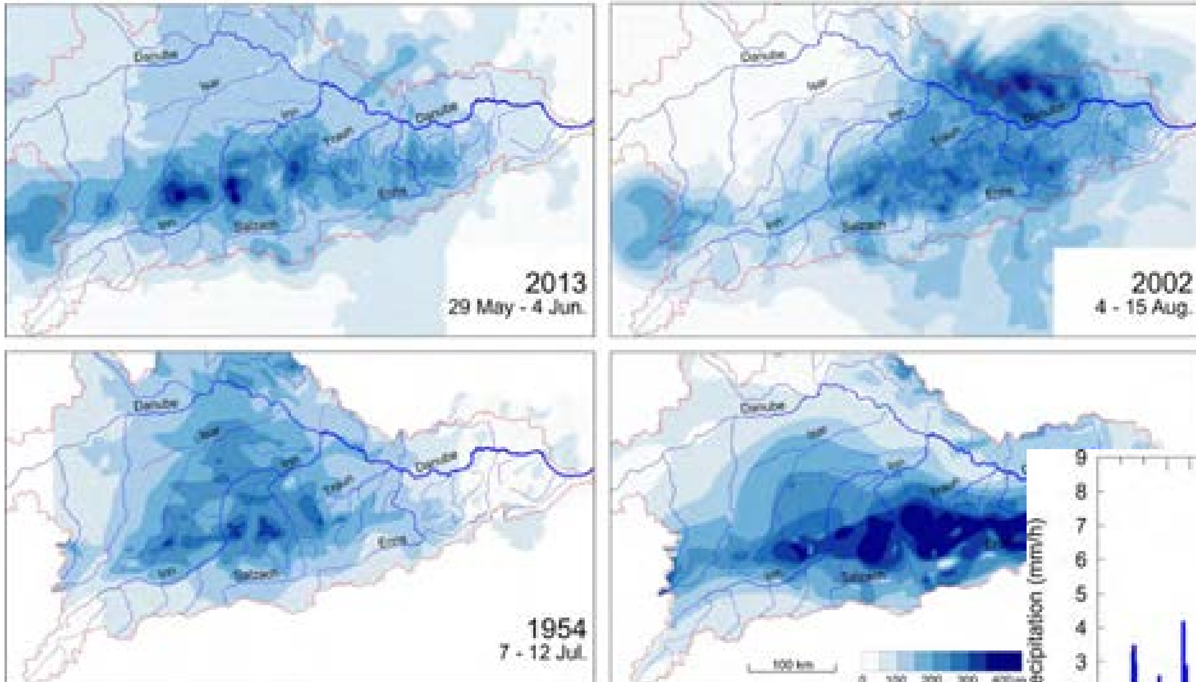
Marks et al., 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrol. Process.* **12**
McCabe et al., 2007. Rain-on-snow events in the western United States. *Bull. Am. Meteorol. Soc.* **88**
http://en.wikipedia.org/wiki/Willamette_Valley_Flood_of_1996

2013 Danube floods

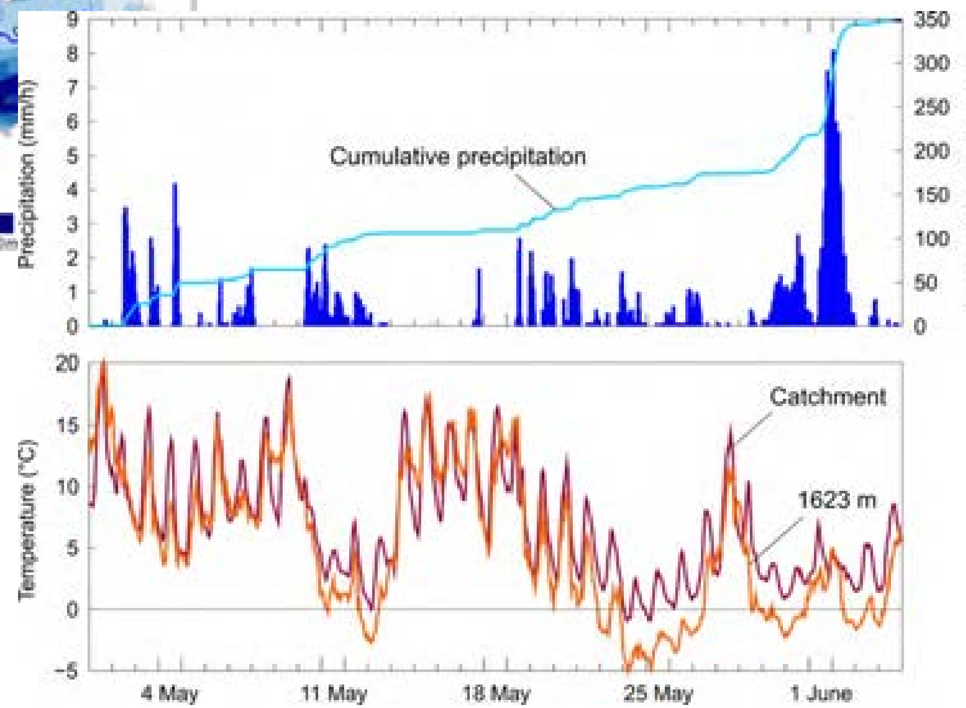
Passau, Germany

Deggendorf, Germany

2013 Danube floods



Most of the precipitation fell along the pre-Alps, in line with events that caused other historical floods.



After a wet May, a final intense precipitation event triggered wide-spread flooding. Because parts of the basin experienced sub-zero temperatures, part of the precipitation fell as snow, thus reducing the potential discharge

Blöschl et al. (2013), *Hydrol. Earth Syst. Sci* **17**

Snowfall in hydrological models

In hydrological models, precipitation has to be divided into rain (liquid precipitation P_{rain}) and snow (solid precipitation P_{solid}) based on temperature. The transition is often gradual and depends on atmospheric conditions.

Above a maximum temperature of 2–3°C, no snow is possible. Below a minimum temperature of −0.5–0.5°C, all precipitation typically falls as snow. In between, the fraction of snow is often assumed to vary linearly.

$$P_{solid} = P_{obs} \qquad T_{air} \leq T_{min}$$

$$P_{solid} = P_{obs} \times (T_{max} - T_{air})/(T_{max} - T_{min}) \qquad T_{min} < T_{air} < T_{max}$$

$$P_{solid} = 0 \qquad T_{air} > T_{max}$$

Andreadis et al., 2009. Modeling snow accumulation and ablation processes in forested environments. *Water Resour. Res.* **45**.

Degree-day snowmelt modeling

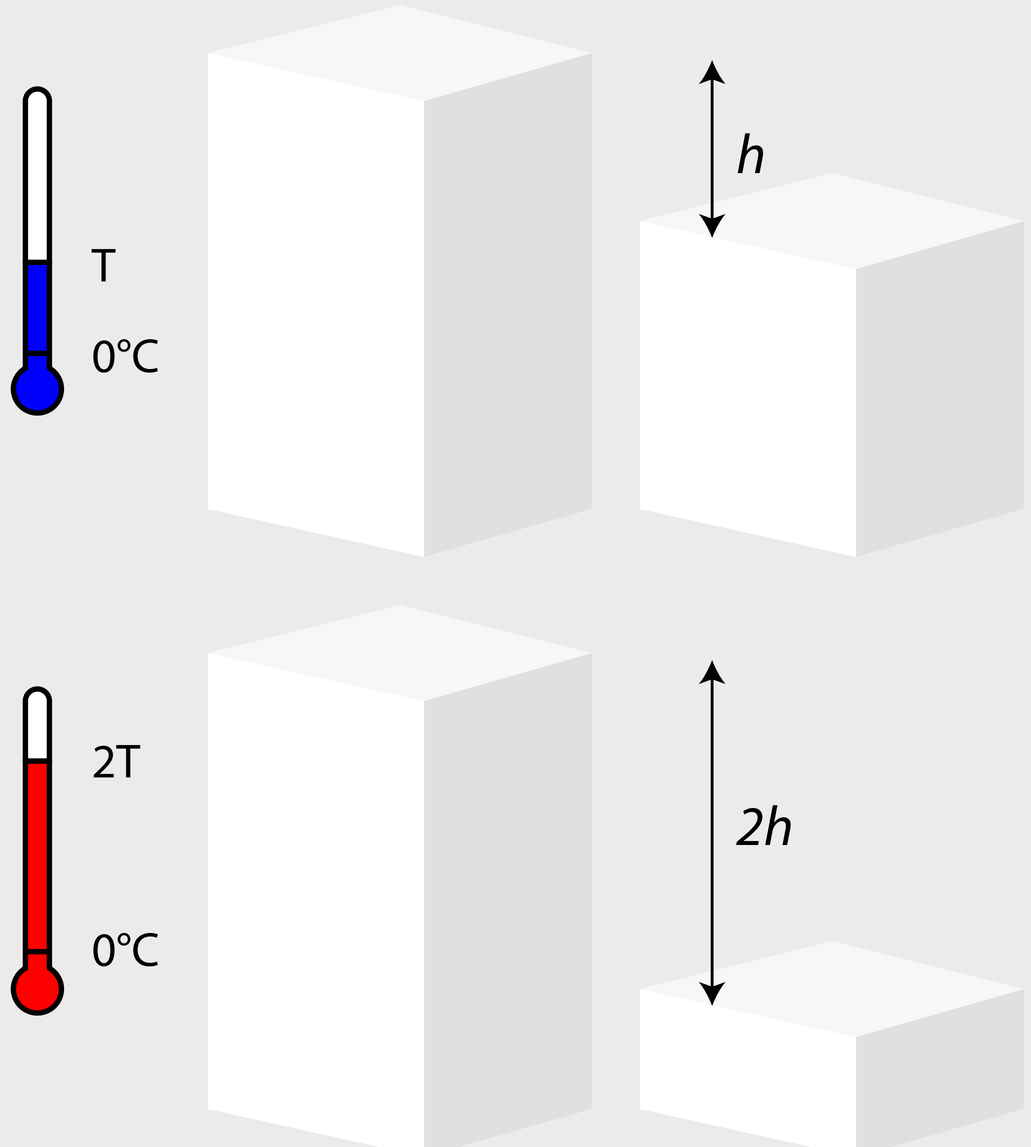
Temperature has a high correlation with radiation, wind and humidity, all factors that influence heat transfer to snowpack. It is easy to measure and extrapolate.

There is often no significant melt below freezing point (0°K).

Cumulative snowmelt is often assumed to be proportional to the number of **degree-days** or **degree-hours**.

The proportionality constant is called the degree-day factor.

Example: 7 days of 6°C gives 7×6 = 42 degree days



Degree-day melt parameters

The daily melt M (mm °C^{-1} day^{-1}) according to the degree-day model is given by:

$$M = \alpha (T_{air} - T_0)$$

where α is the degree-day factor and T_0 the baseline temperature (often 0°C).

The factor α depends primarily on the density of the snow :

$$\alpha = 11\, \rho_{snow}/\rho_{water}$$

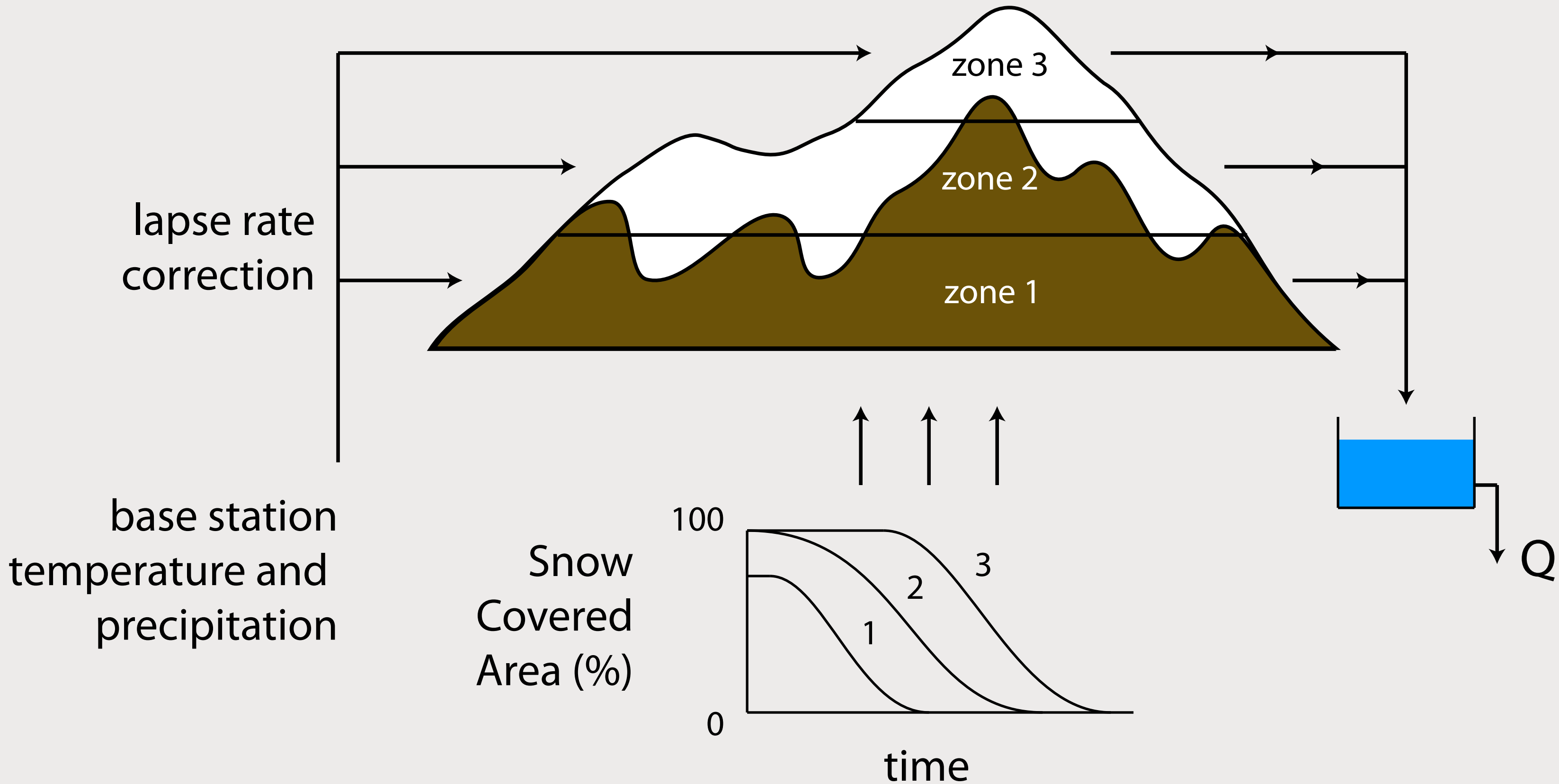
so that higher melting is found for compacted snow.

Degree-day factors

Snow	3.5–6 mm °C^{-1} day^{-1}
(Glacier) Ice	6–11 mm °C^{-1} day^{-1}

Martinec and Rango, 1986. Parameter values for snowmelt runoff modeling. *J. Hydrol.* **84**
Singh et al. 2000. Degree–day factors for snow and ice for Dokriani Glacier, Garhwal Himalayas. *J. Hydrol.* **235**

The Snowmelt Runoff Model (SRM)



SRM has been developed to predict daily snowmelt runoff in mountainous terrain. It subdivides a basin in several elevation zones, and calculates snow-melt based on the degree-day concept and conventional depletion curves describing the evolution of snow covered area in time.

Martinec, 1975. Snowmelt-runoff model for stream flow forecasts. Nordic Hydrol. **6**

The Snowmelt Runoff Model (SRM)

The original version of SRM could be represented by a single equation:

$$Q_{n+1} = kQ_n + (1-k)\sum_i(a_i T_i A_i + P_i)$$

where k is a recession coefficient, a_i the degree-day factor , and A_i the snow covered area for each elevation zone (subscript i).

The current version is slightly more complicated and involves correction factors for losses from snowmelt (c_{Sn}) and precipitation (c_{Rn}):

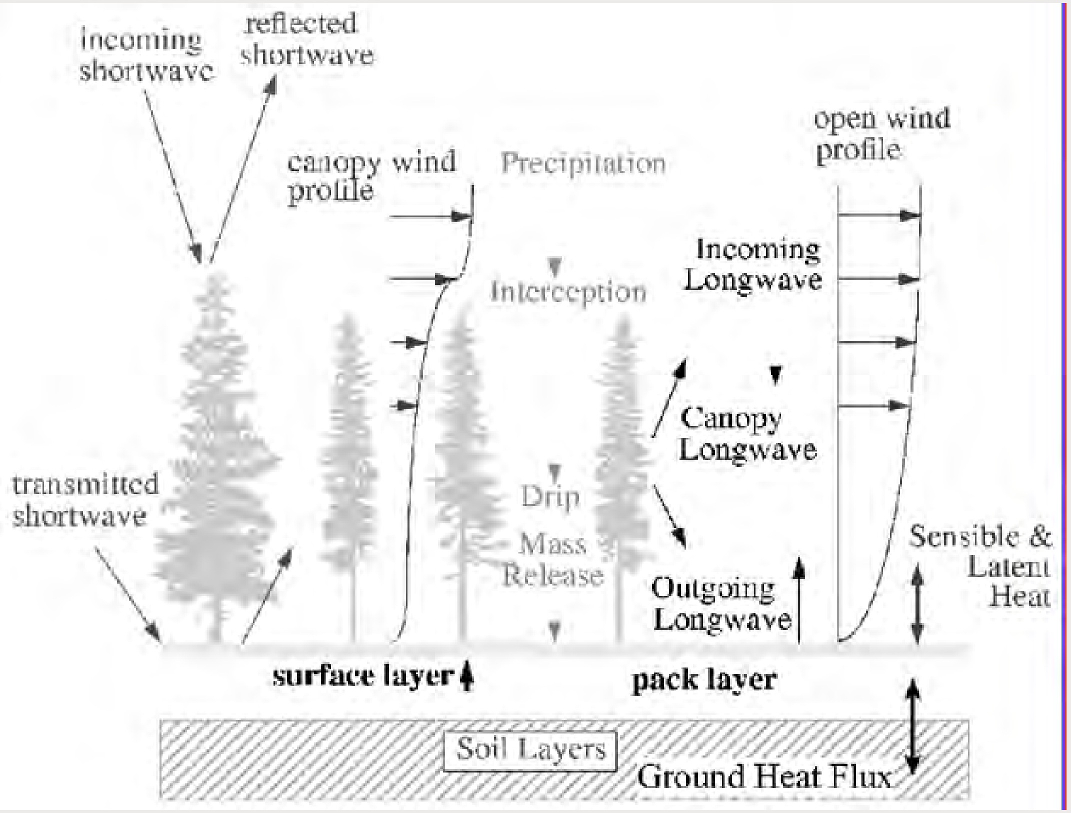
$$Q_{n+1} = k_{n+1}Q_n + (1-k_{n+1})\sum_i(c_{Sn} a_i T_i A_i + c_{Rn} P_i)$$

In principle, only k needs to be calibrated from catchment discharge data.

Martinec, 1975. Snowmelt-runoff model for stream flow forecasts. *Nordic Hydrol*. **6**
http://www.macaulay.ac.uk/hydalp/private/demonstrator_v2.0/models/srm.html

Physically-based snowmelt modeling (VIC)

Physically-based land surface models like the Variable Infiltration Capacity model (VIC) often contain snow modules based on energy balance principles.

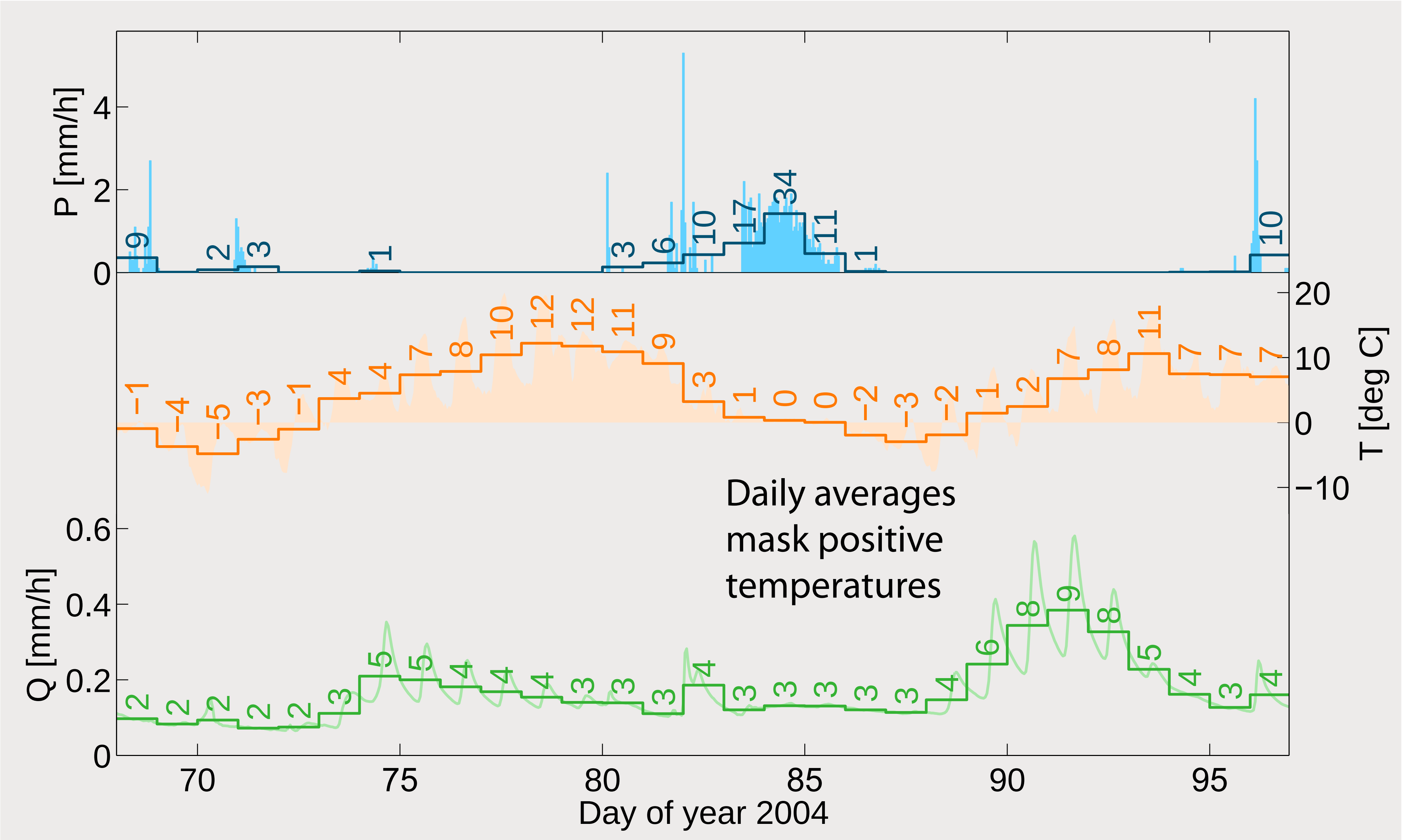


Snow albedo is a key parameter controlling the available energy for melt. Fresh snow reflects 80-90% of the received sunlight, whereas this fraction reduces strongly in older or melting snow (40-80%).

The roughness of the snowpack is another sensitive parameter: it controls the exchange of heat between the atmosphere and the snowpack.

Andreadis et al., 2009. Modeling snow accumulation and ablation processes in forested environments. *Water Resour. Res.* **45**.

Example: Rietholzbach Spring 2004



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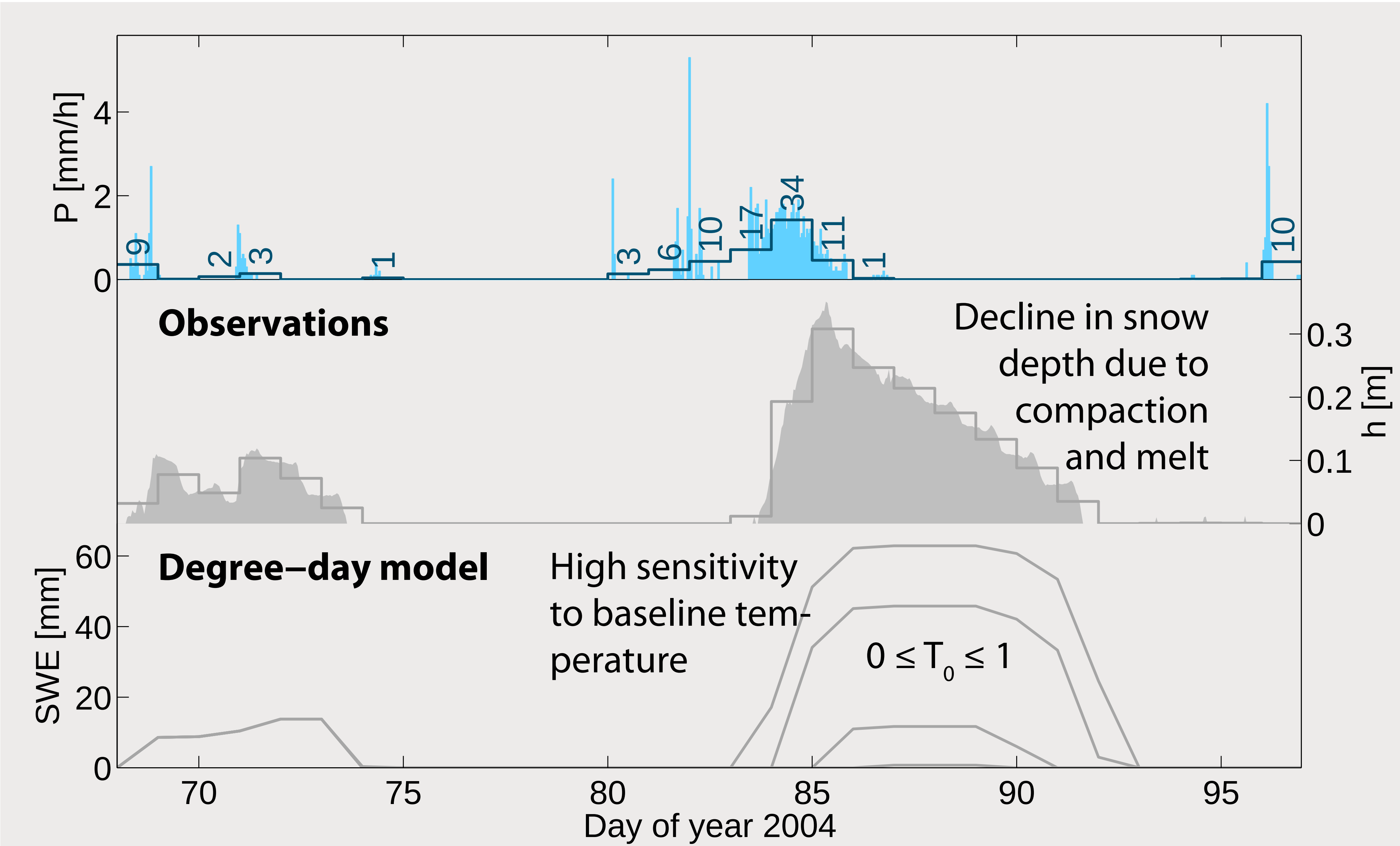
Example: Rietholzbach Spring 2004



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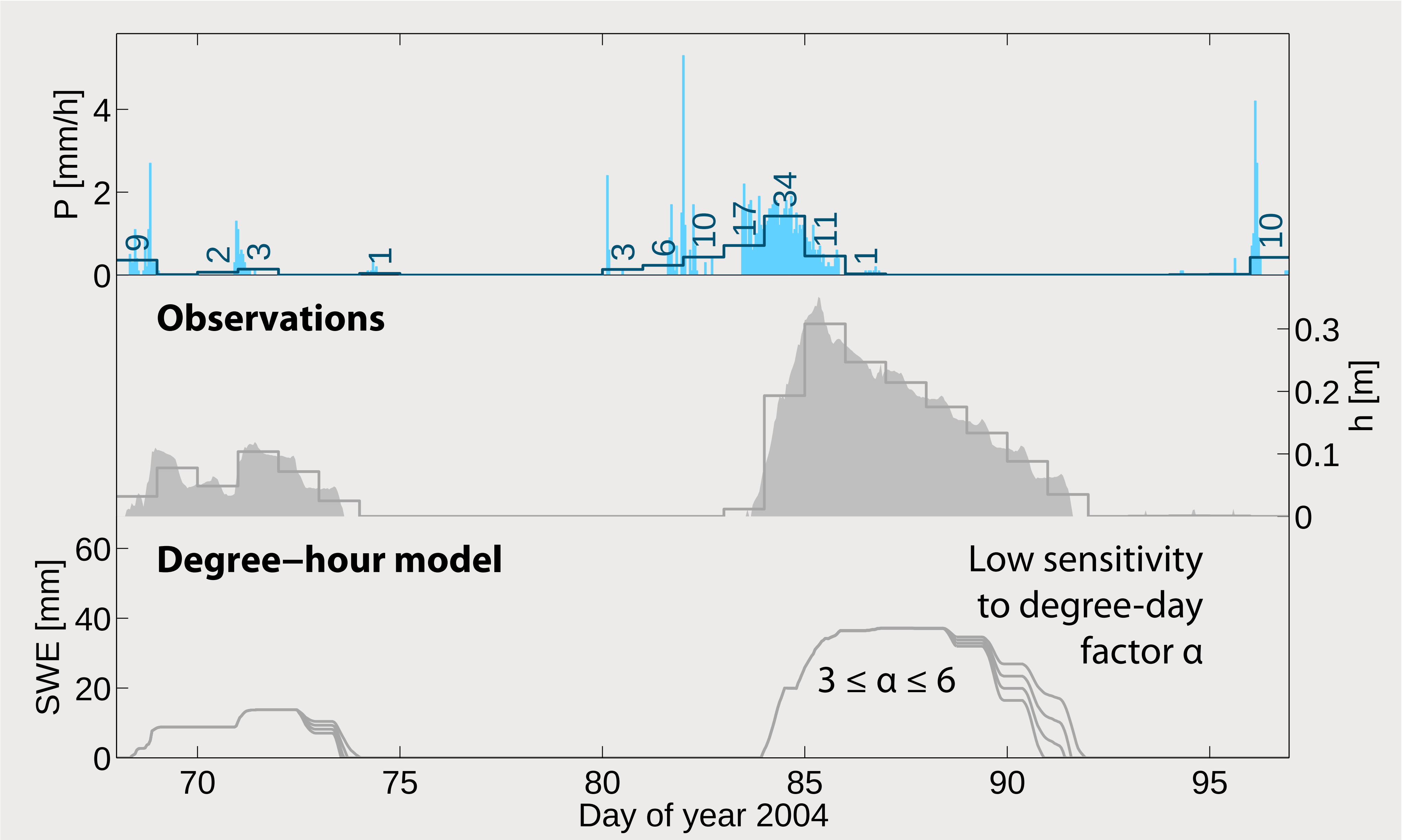
Example: Rietholzbach Spring 2004



Seneviratne et al., 2012. Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event. *Water Resour. Res.* **48**

Snow cover and aspect at Rietholzbach

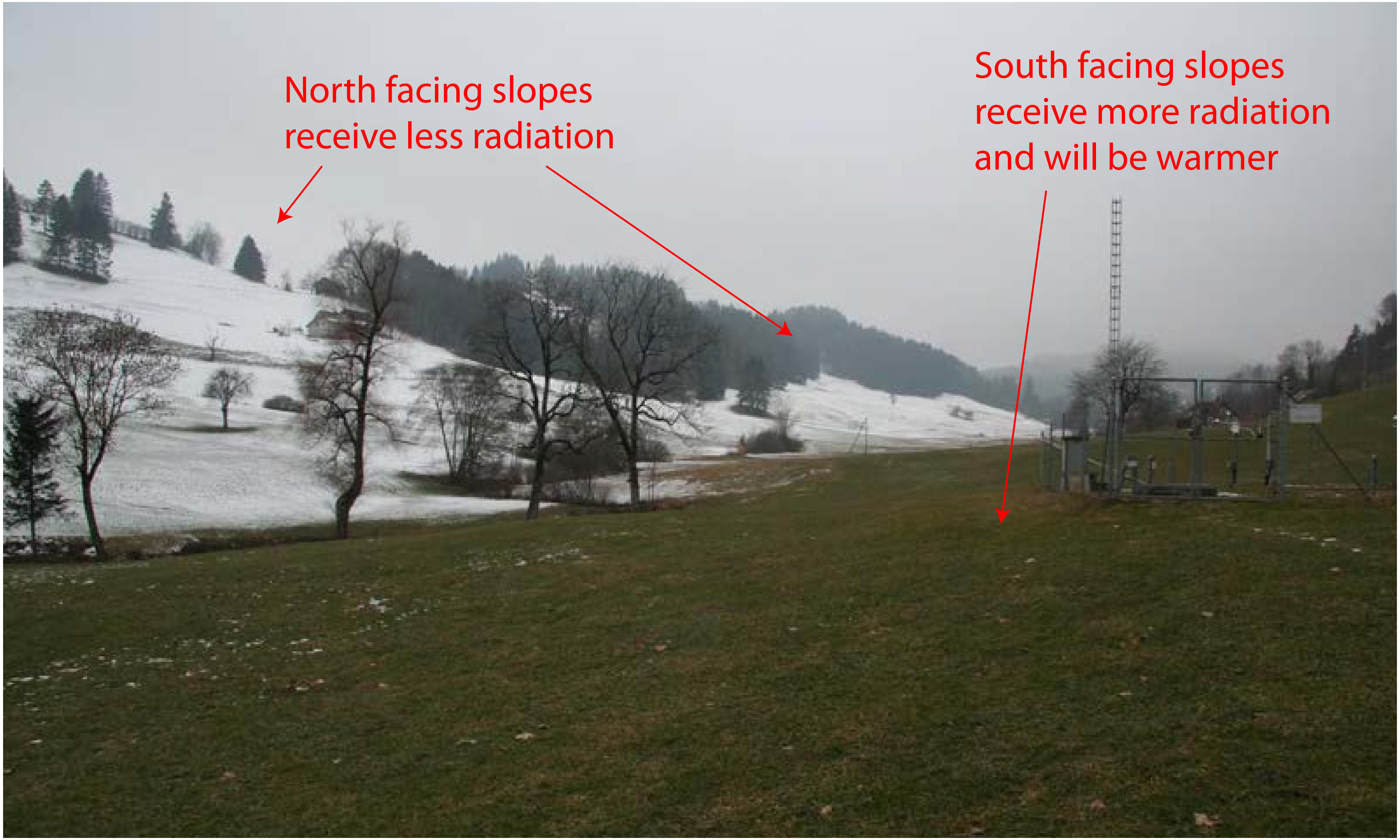
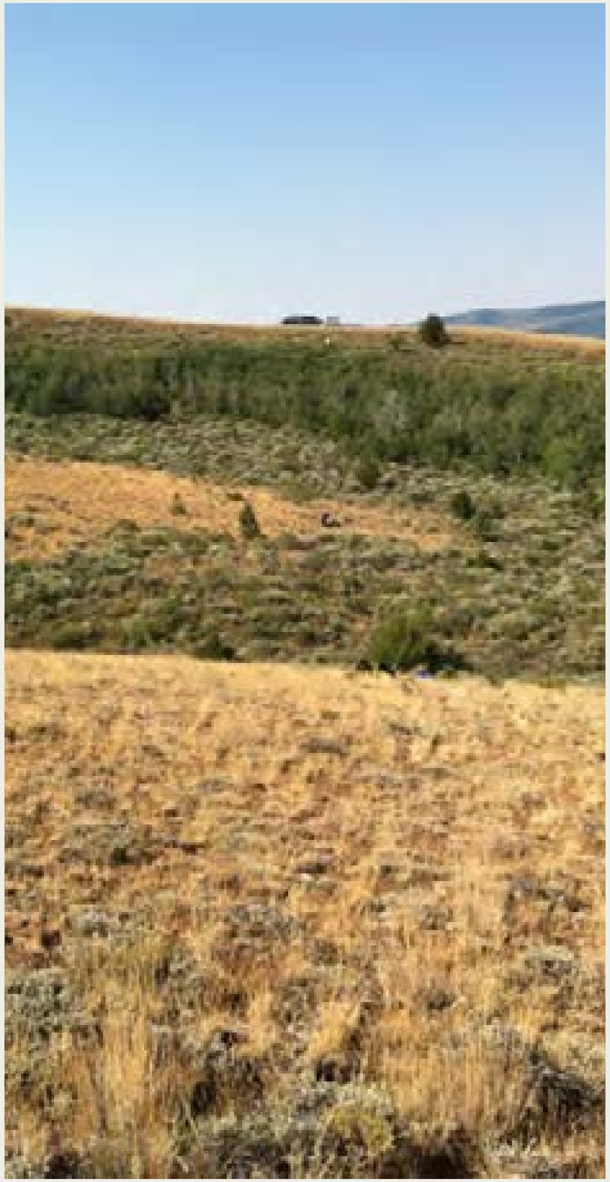
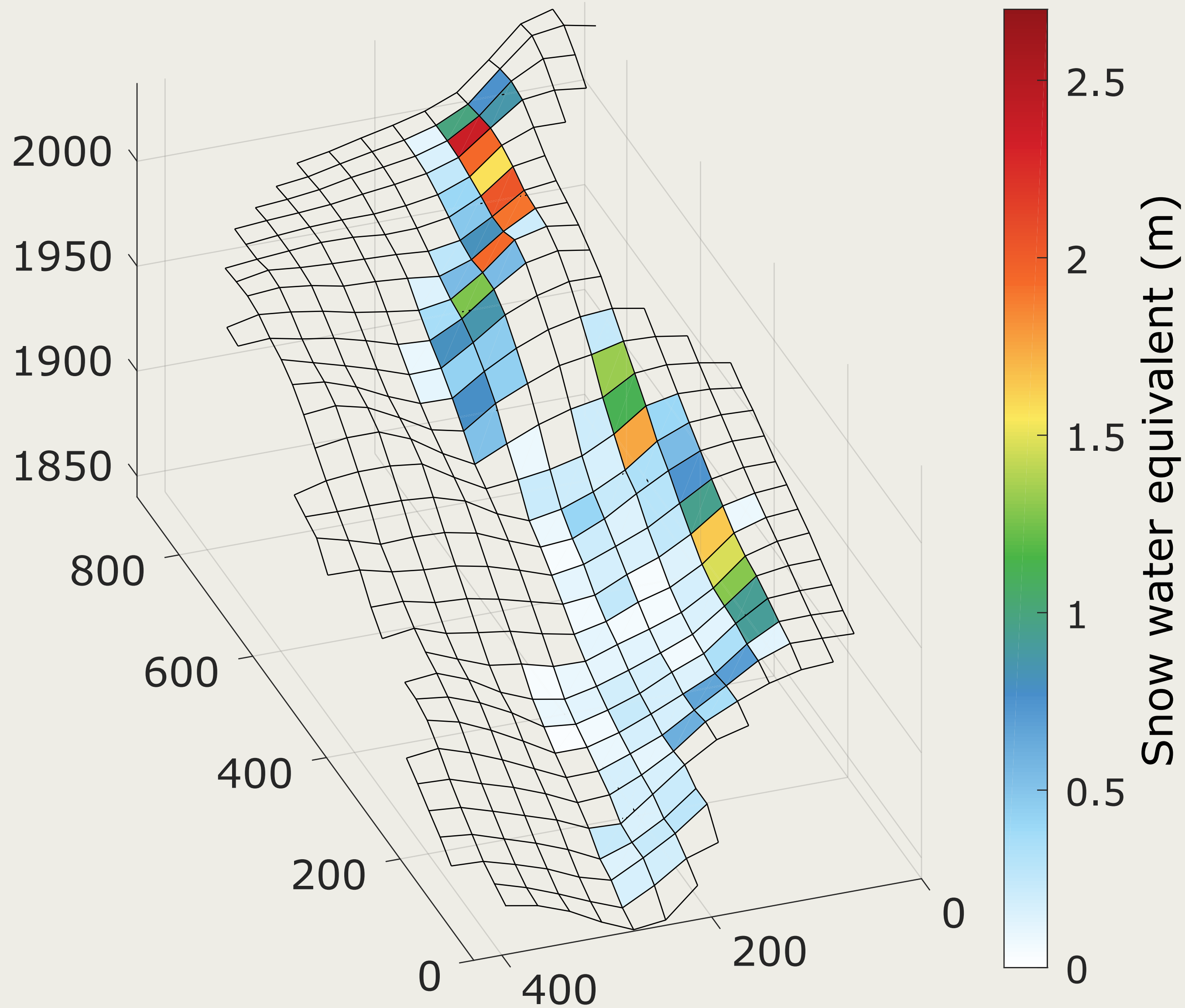


photo: Irene Lehner, ETH Zurich

Upper Sheep Creek experiment (Idaho)





Prasad et al. (2001), *Water Resour. Res.*, **37**

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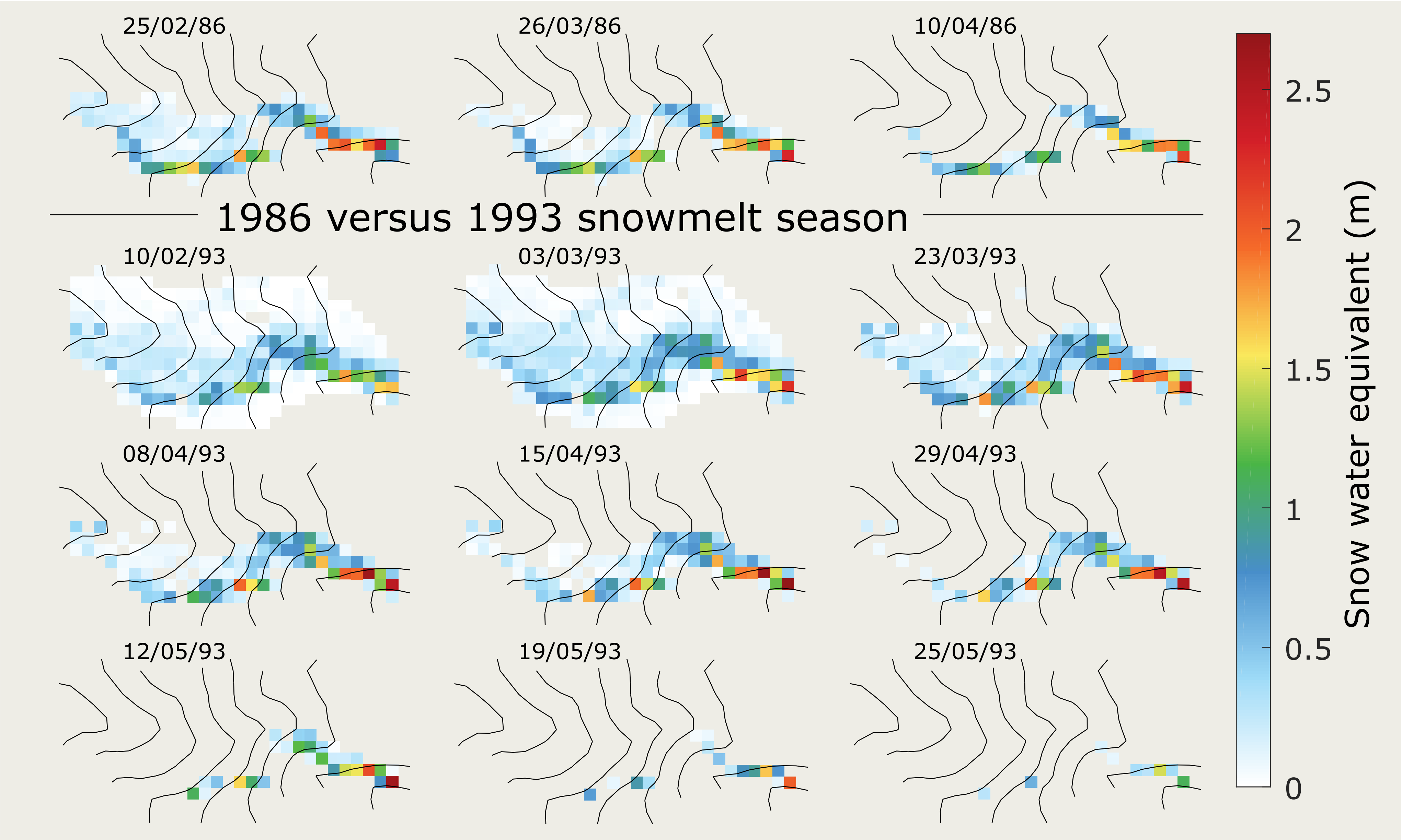
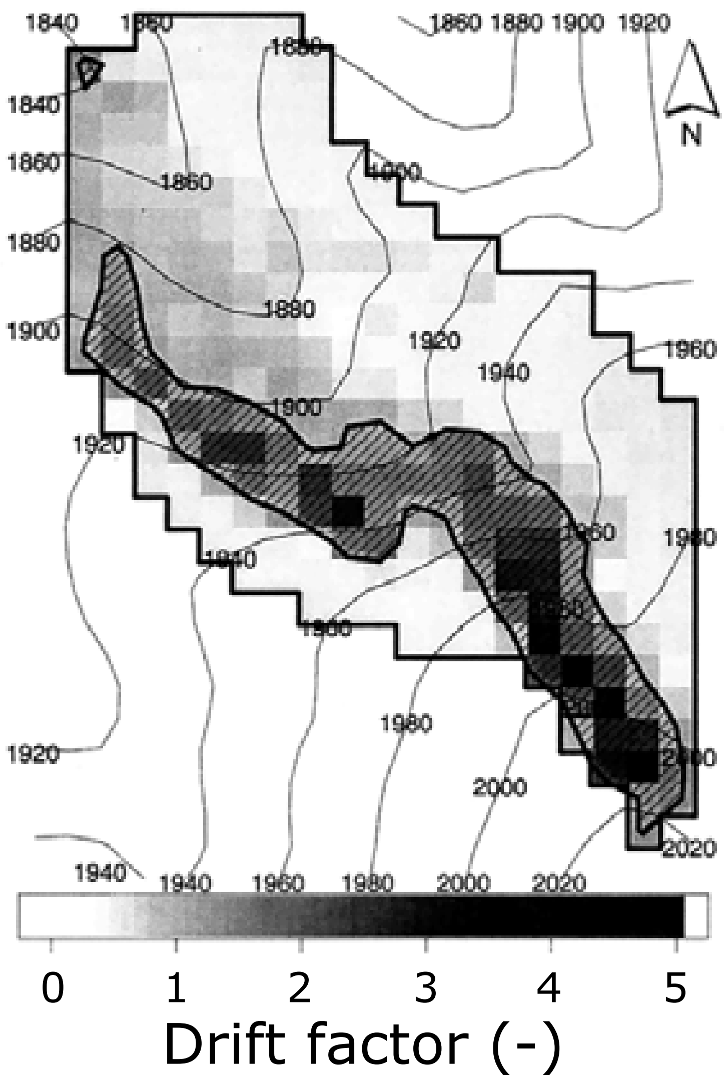
Preferred snow water equivalent patterns



Prasad et al. (2001), *Water Resour. Res.*, **37**

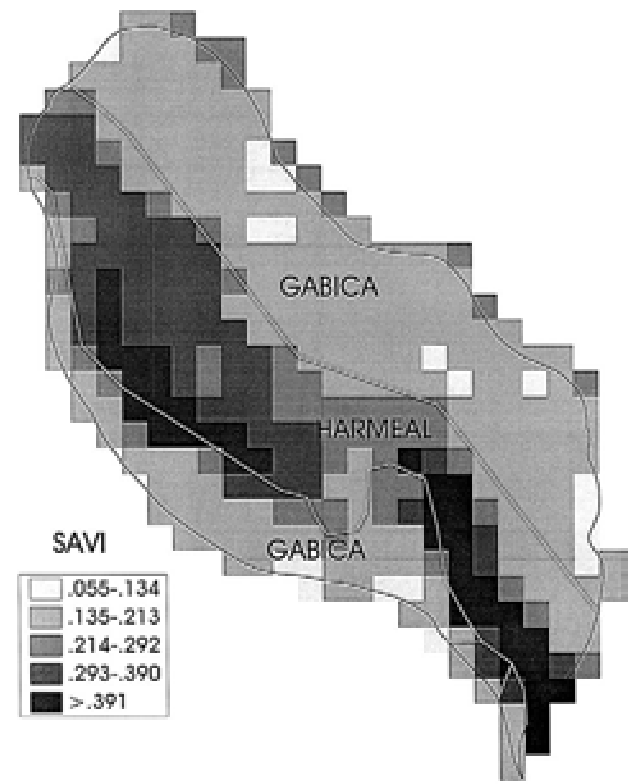
Snow drift, soil and vegetation patterns



Snow accumulation is expressed by the **drift factor**, which is the local snow accumulation normalized by the gauge-measured accumulation. In Upper Sheep Creek the drift factor is highly variable.

The pattern of Soil Adjusted Vegetation Index and soil types closely resembles average snow drift.

Snow drift likely a main determinant of dry-season water availability and soil formation.



Seyfried (1998), *Geoderma* **85**
Prasad et al. (2001), *Water Resour. Res.* **37**

Patterns due to snow drift at Landmannalaugar

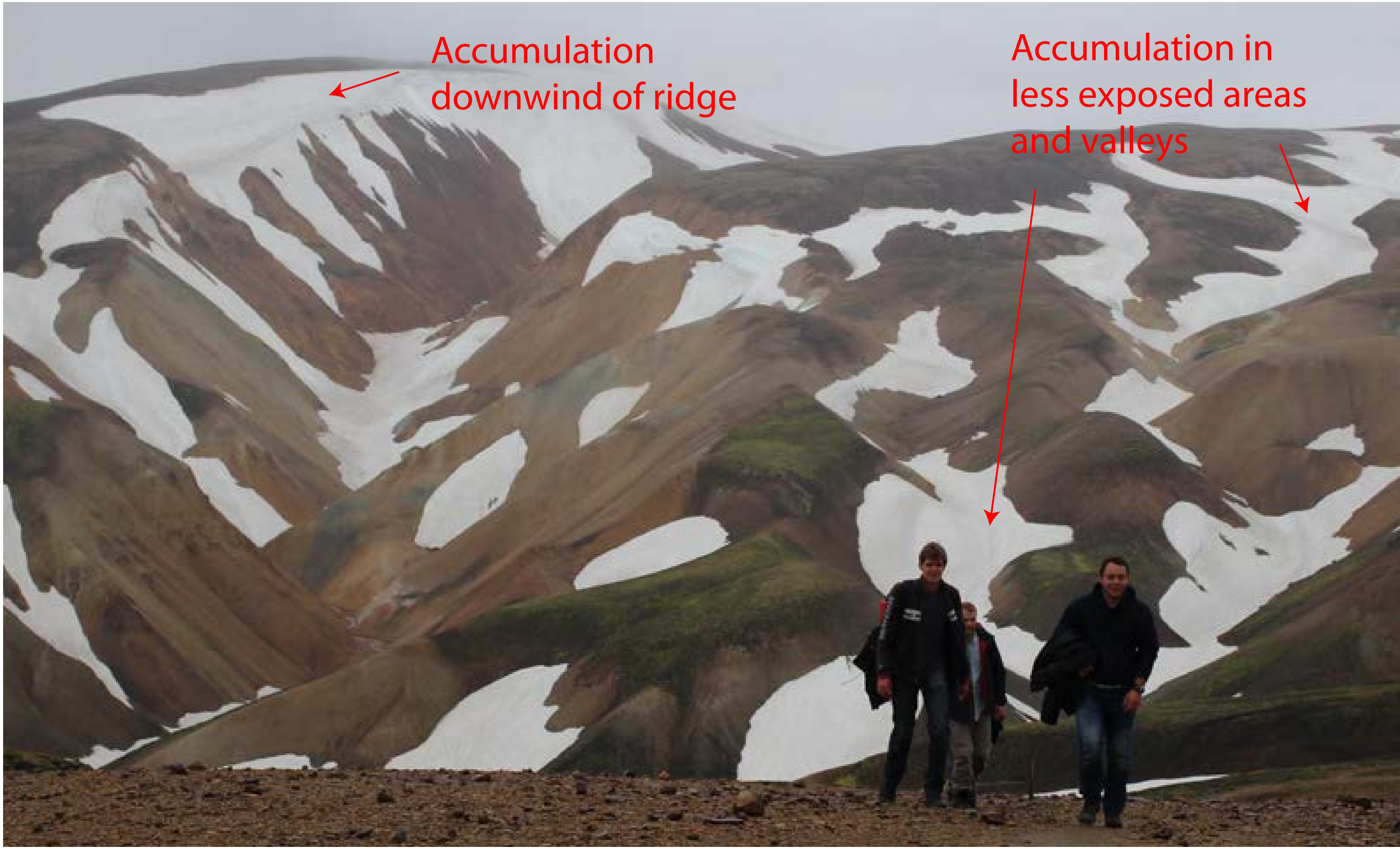
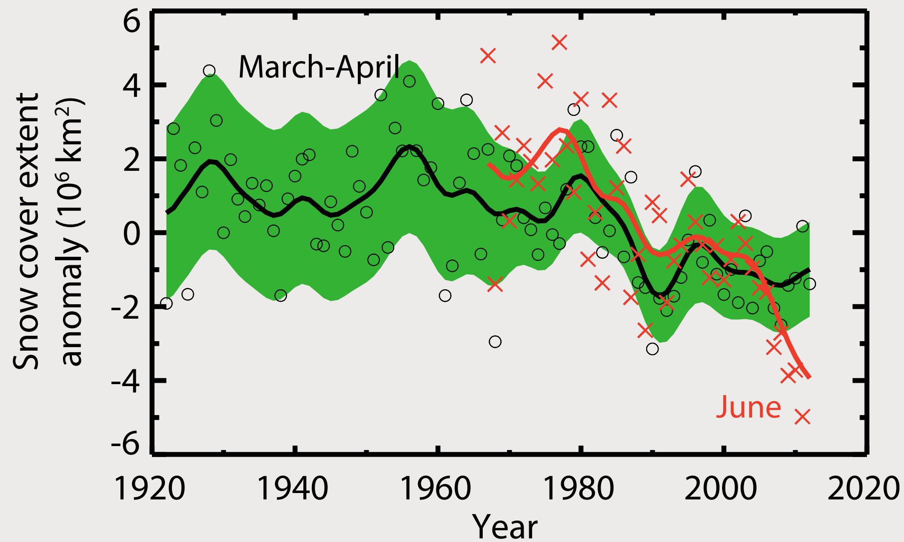
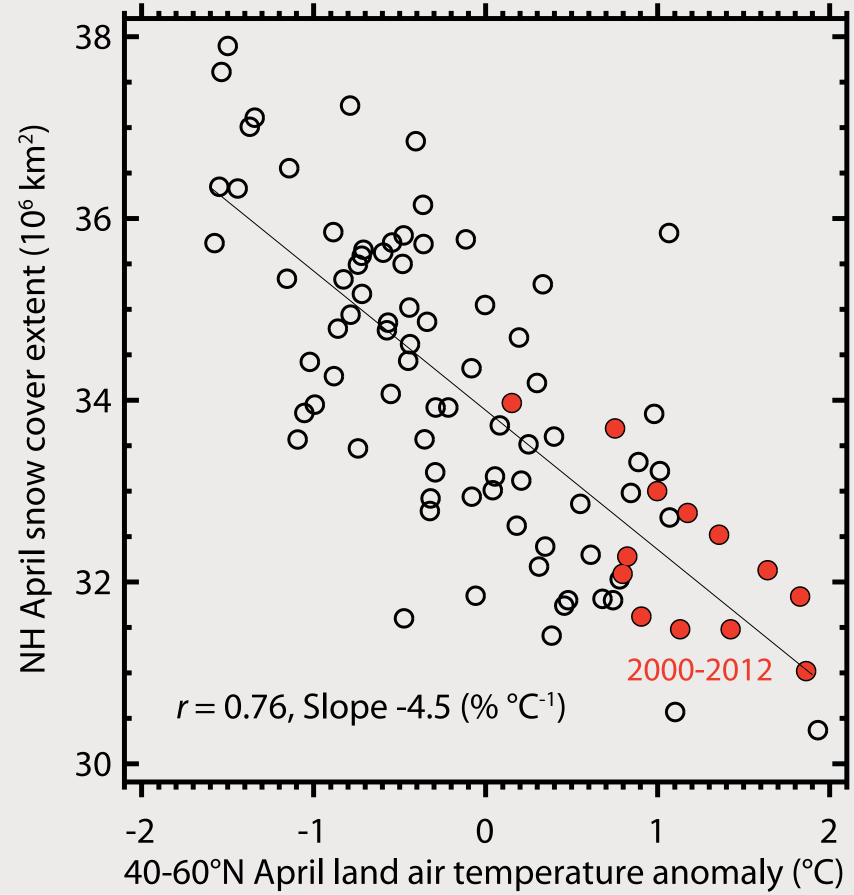


photo: Iceland excursion 2015 (Ryan Teuling)

Climate change and snow cover: IPCC AR5





Northern Hemisphere Spring snow cover decreased significantly (*very high confidence*) due to snow-albedo feedback.

Vaughan et al. (2013), Observations: Cryosphere. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker et al. (eds.)]. Cambridge University Press.
updated from Brown and Robinson (2011), Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty. *Cryosphere* **5**

Warming trend spoils Europe's w

https://www.nature.com/articles/d41586-018-07321-0

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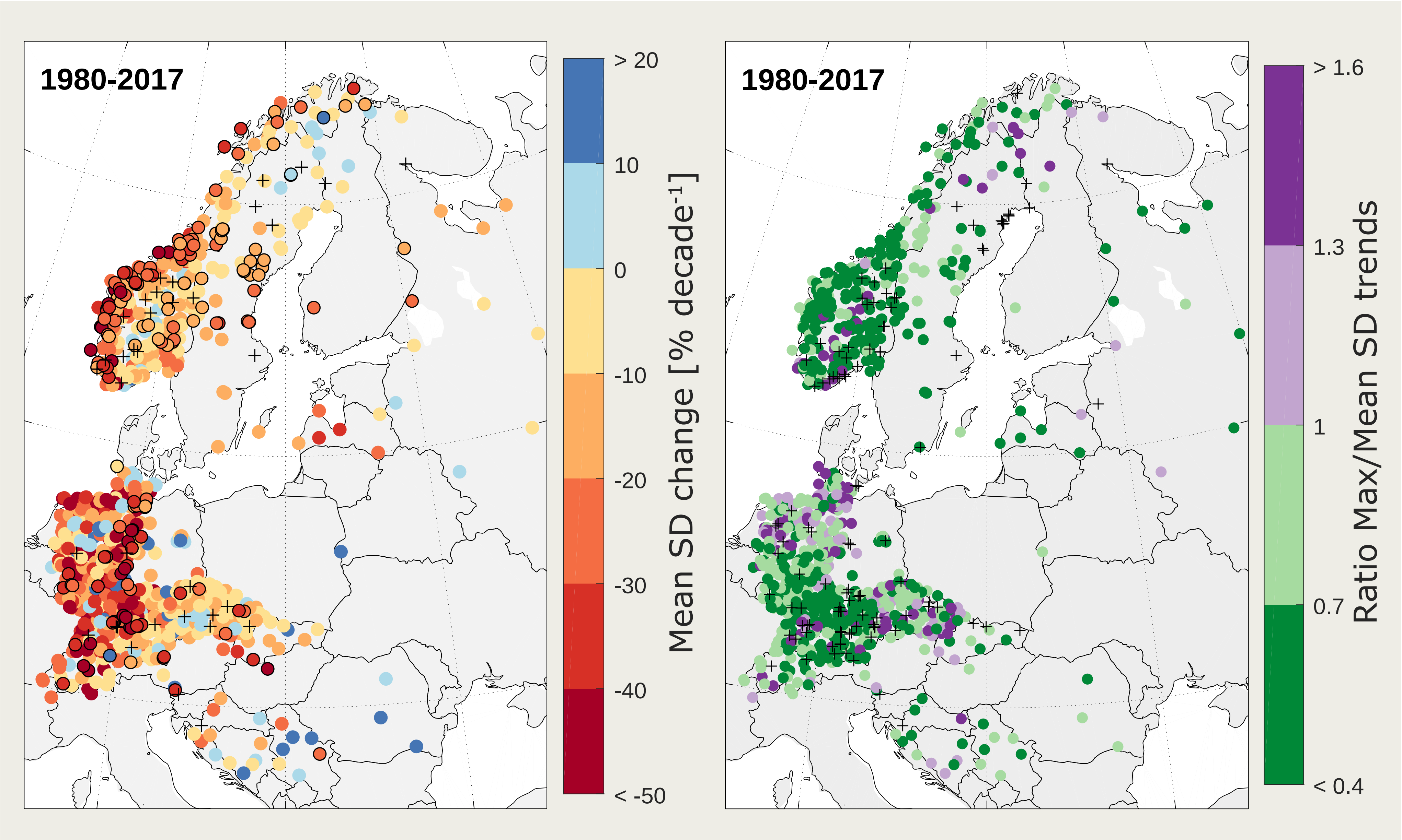
Snowboarders in the Swiss Alps make the best of a meagre snow layer, an example of the decrease in snow depth across Europe. Credit: Fabrice Coffrini/AFP/Getty

CLIMATE SCIENCES · 06 NOVEMBER 2018

Warming trend spoils Europe's winter wonderlands

The thick snowdrifts of years gone by could become a rarity across the continent.

Mean vs. maximum snow depth changes



Fontrodona Bach et al. (2018), *Geophys. Res. Lett.* **45**

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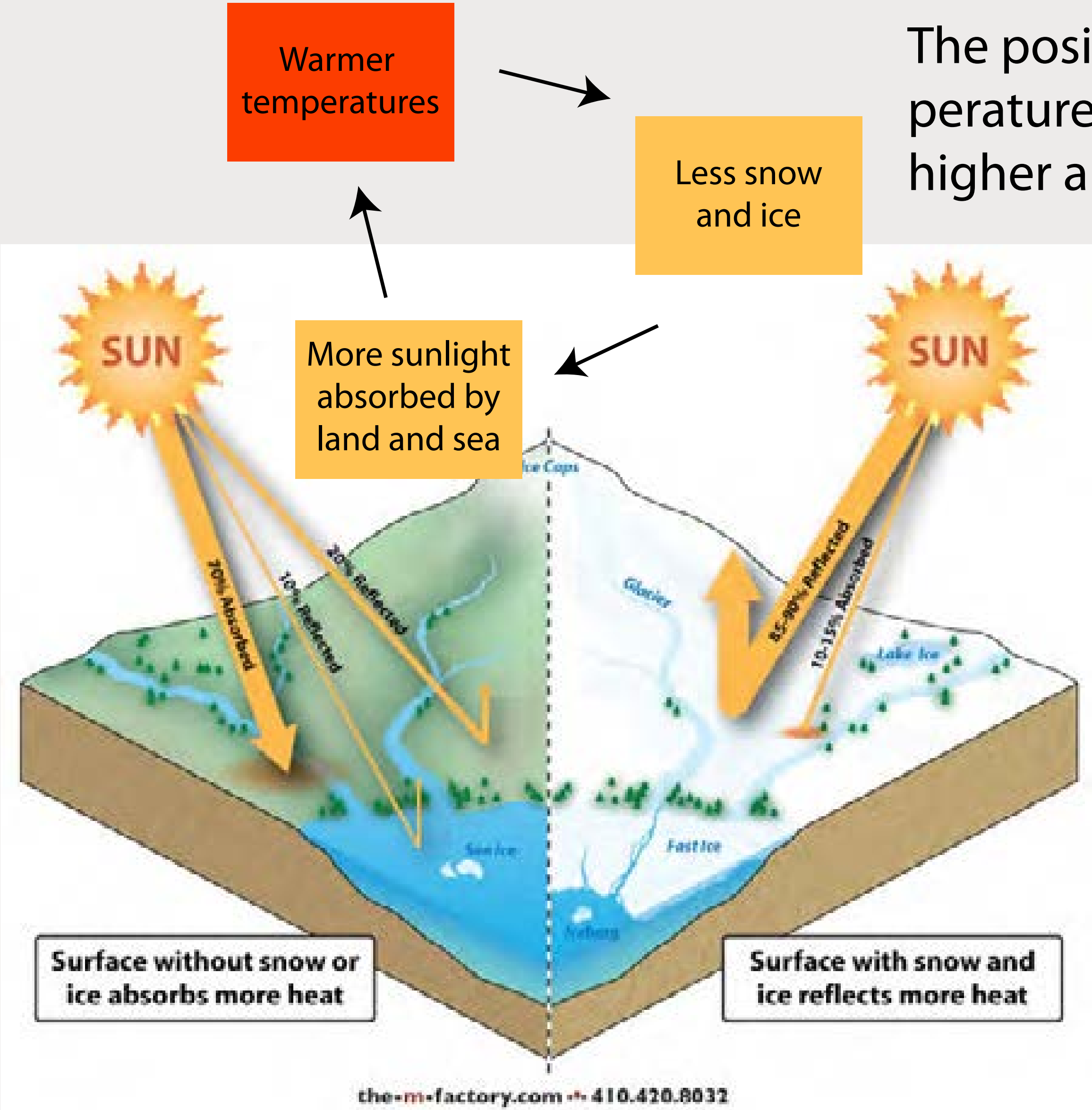
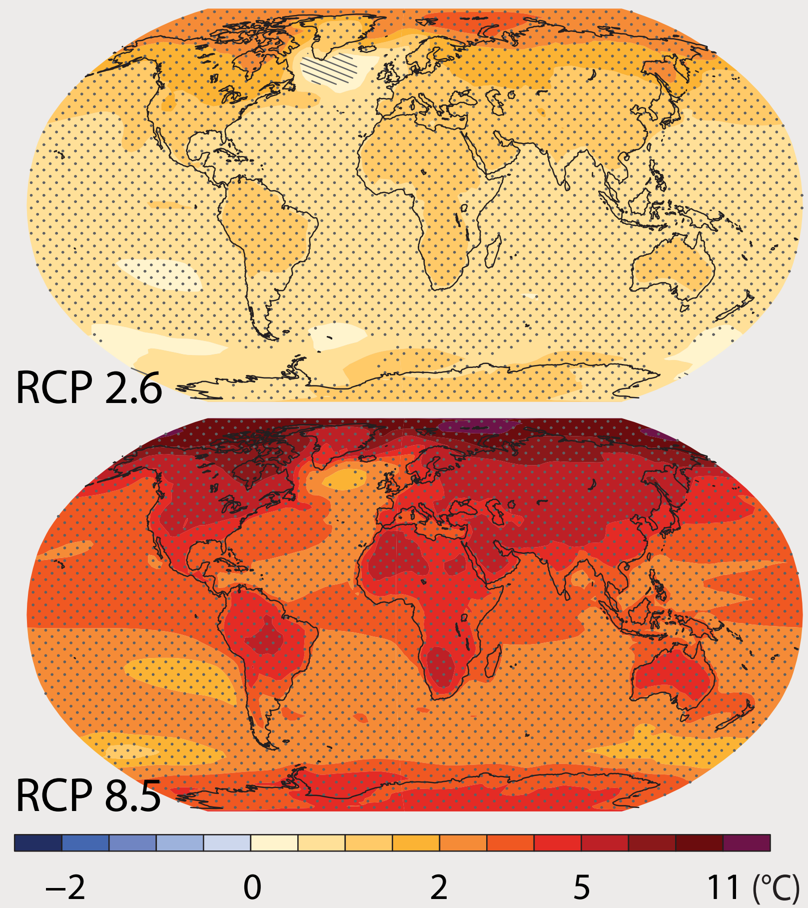
Snow-albedo feedback and arctic amplification



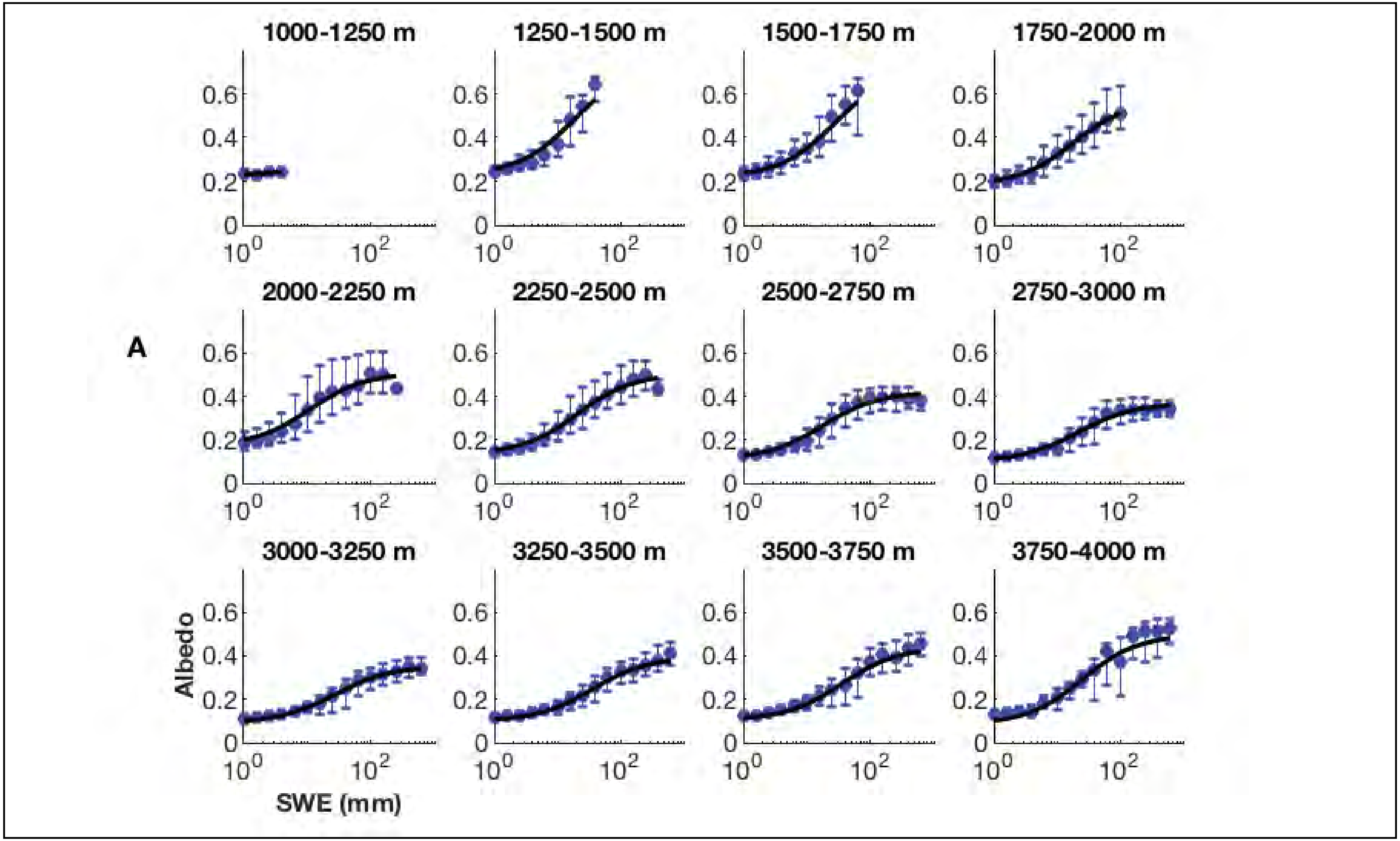
The positive feedback between higher temperatures and reduced snow cover leads to higher arctic temperatures.



https://www.ipcc.ch/index.htm

Upper Colorado River Basin (UCRB)

Albedo strongly depends on snow amount



Milly & Dunne (2020), *Science* **367**

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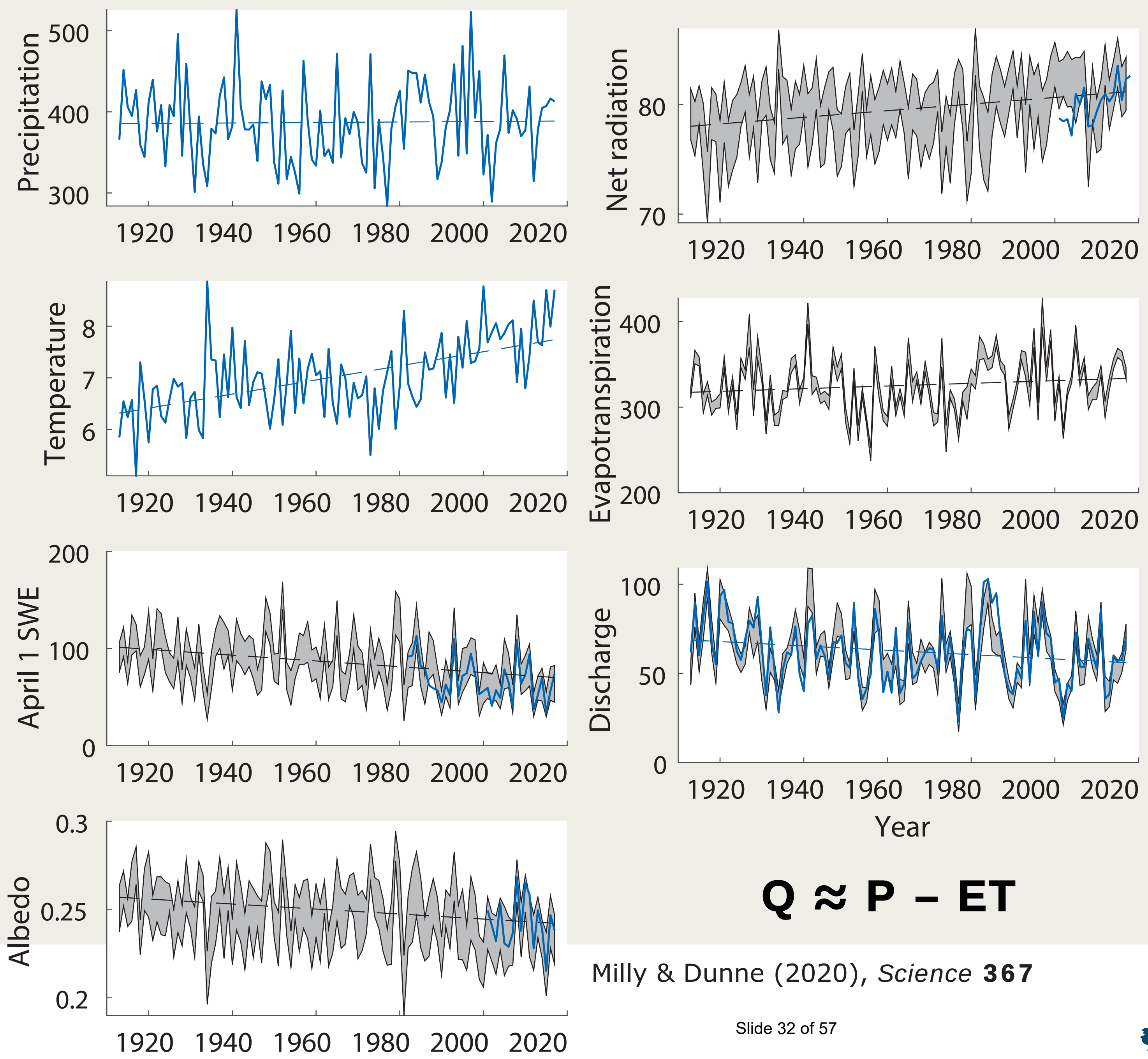
Changes in UCRB hydroclimatology

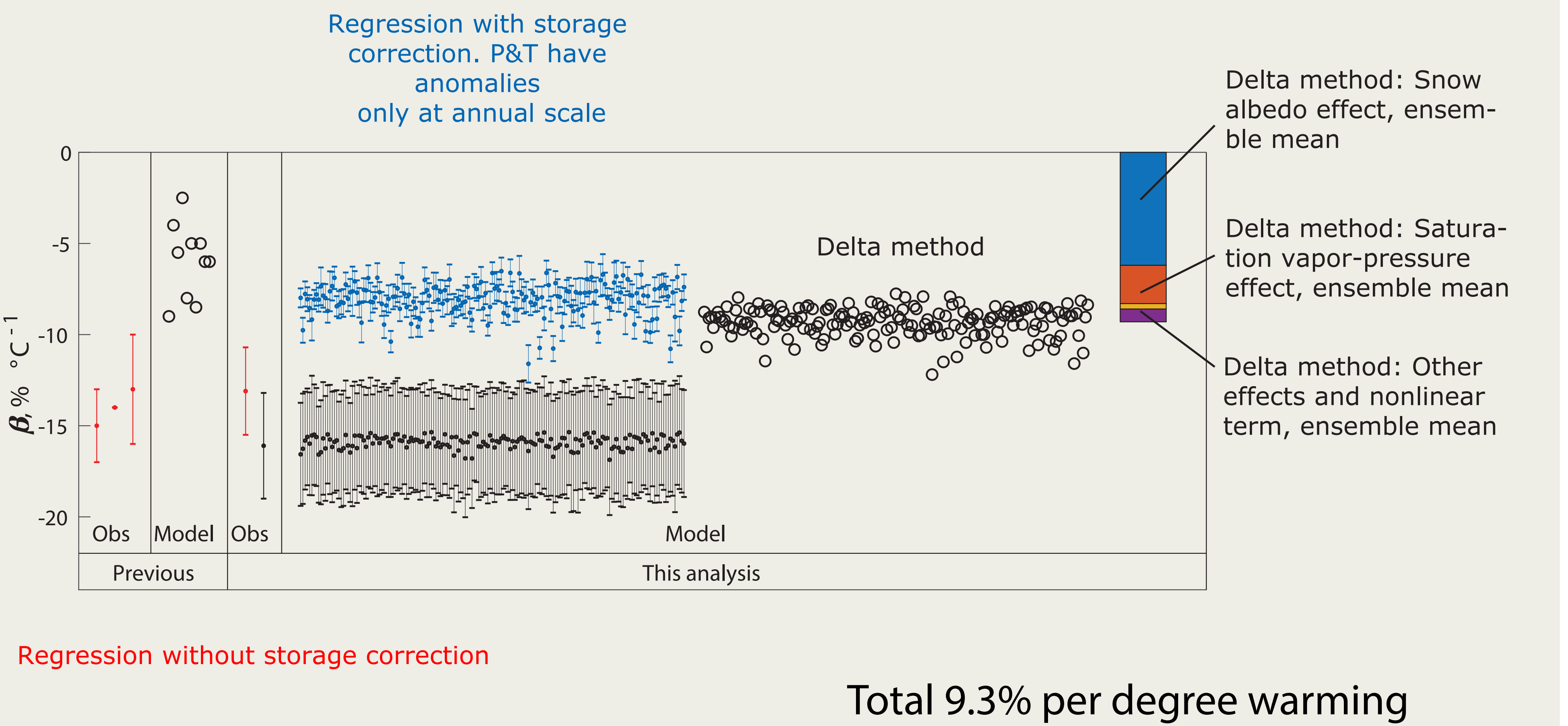


Increasing temperature leads to a decrease of SWE and albedo, leading to a net radiation decrease of 3%. With an associated increase in evapotranspiration, the ensemble mean annual discharge fell by 20.1% per century, compared with 19.6% observed.

Q ≈ P – ET

Milly & Dunne (2020), *Science* **367**

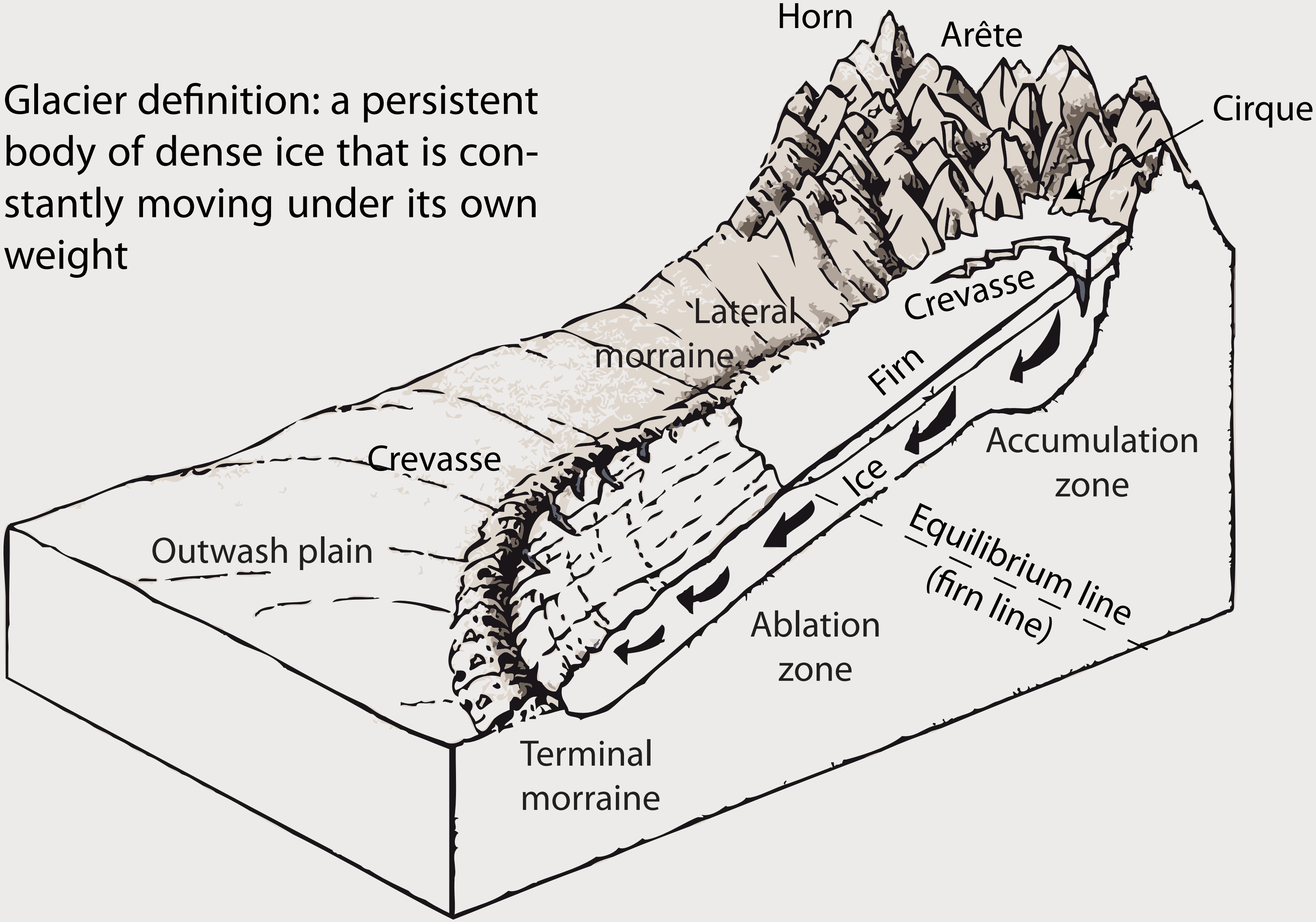
Resolving disparity in sensitivity estimates



Milly & Dunne (2020), *Science* **367**

Alpine glacier anatomy

Glacier definition: a persistent body of dense ice that is constantly moving under its own weight



adapted from yosemite.ca.us
http://en.wikipedia.org/wiki/Glacier

Equilibrium line and cirque limit

Rolleston glacier, Southern Alps, New Zealand

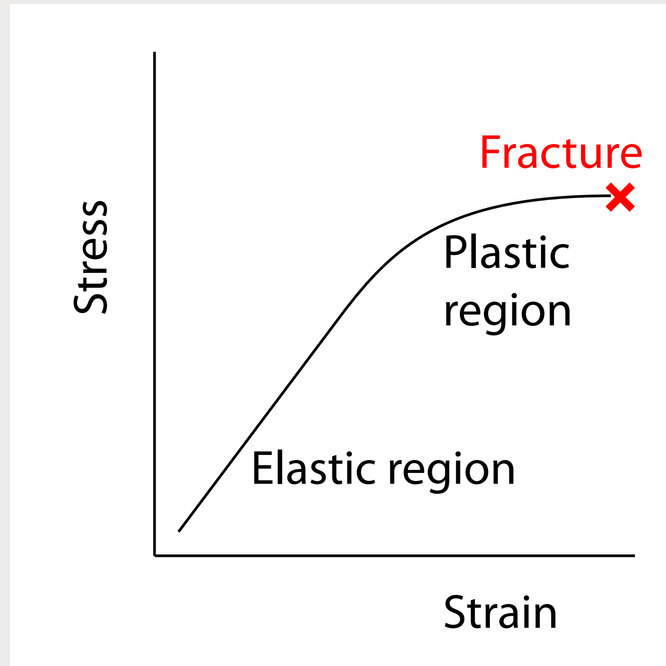
Flow of glacier ice

Ice can deform and flow under pressure (stress)

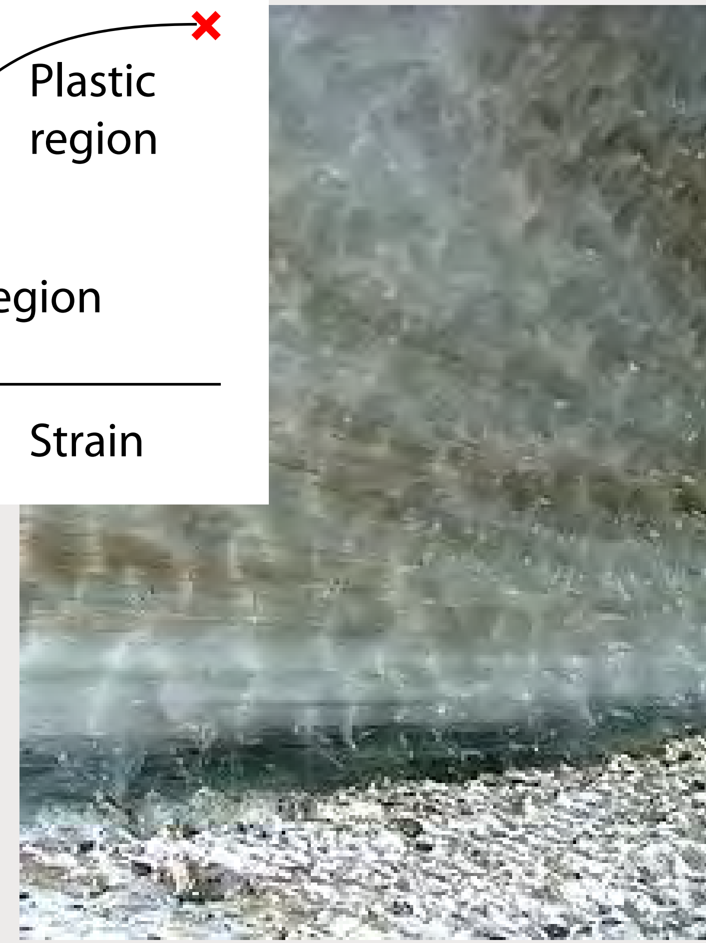
The movement is characterized by plasticity, the property of a material to undergo permanent deformation under pressure.

In contrast to liquid flow, the shear stress at the glacier base will always be equal to the yield stress τ_0.

Ice sheets thinner than 30 m will not flow, in ice of more than 50 m thickness, small amounts of stress will result in large amounts of strain.



Glacier base



http://en.wikipedia.org/wiki/Ice-sheet_dynamics

Glaciers in Iceland

Name	Area (km^2)		Volume (km^3)
Vatnajökull	8,300		3,100
Langjökull	953		195
Hofsjökull	925		208
Mýrdalsjökull	596		140
Drangajökull	160		
Eyjafjallajökull	78		
Tungnafellsjökull	48		
Þórisjökull	32		
Eiríksjökull	22		
Þrándarjökull	22		
Tindfjallajökull	19		
...	...		...
Σ	11,181	(11%)	3,600

http://en.wikipedia.org/wiki/Glaciers_of_Iceland

Glaciers in Iceland

Glaciers in Switzerland

Name	Area (km^2)	Length (km) 1850	Length (km) 2010	Volume (km^3)
Aletsch	117.6	26.5	23.6	15.36
Gorner	63.7	16.0	14.5	5.85
Fiesch	39.0	17.1	14.7	3.84
Unteraar	35.5	14.5	13.9	3.75
Lower Grindelwald	27.1	9.9	9.4	3.84
Corbassière	23.0	12.9	10.4	1.48
Oberaletsch	23.0	10.4	9.0	2.21
Rhone	20.9	9.3	7.9	2.11
Findelen	20.6	10.4	8.5	1.89
Gauli	20.5	9.2	6.8	1.05
Morteratsch	19.7	8.9	8.4	1.25
...	...	...	...	...
Σ	1063 (3%)			74

http://en.wikipedia.org/wiki/List_of_glaciers_in_Switzerland
Farinotti et al. (2009) An estimate of the glacier ice volume in the Swiss Alps. *Glob. Plan. Ch.* **68**

Glaciers in Switzerland: Aletsch glacier

Recent changes in glacier length: Rhone glacier

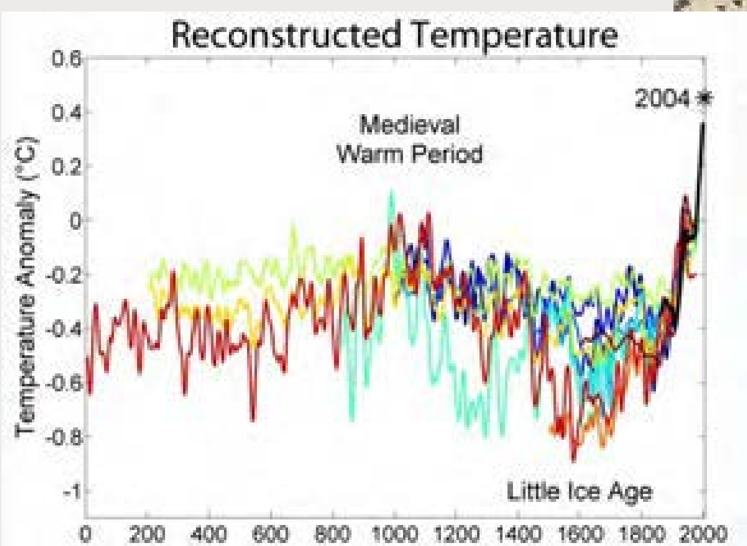
source:
wikipedia

Changes since Little Ice Age: Rhone glacier

1856

1900

2014



Glacier length is controlled both by long-term climate variations and anthropogenic global warming

Two contrasting Swiss catchments

Rietholzbach (Mosnang)

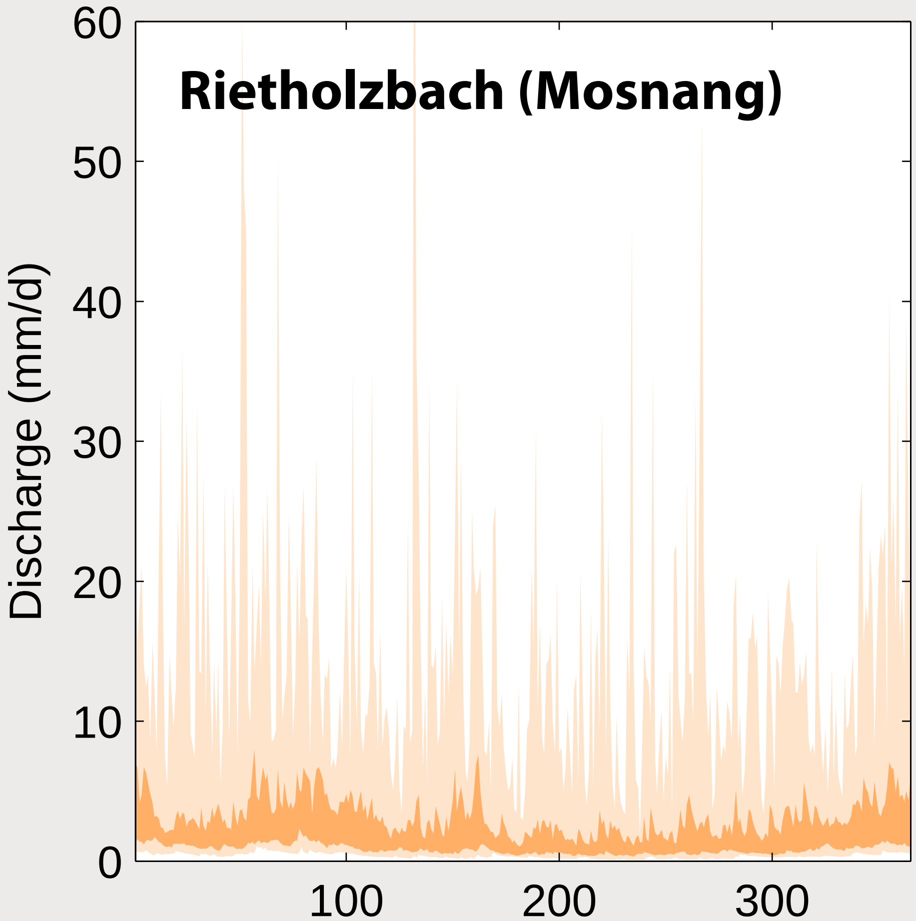
Catchment area	3.31 km^2
Mean elevation	795 m
Glacier area	0%

Rhone (Gletsch)

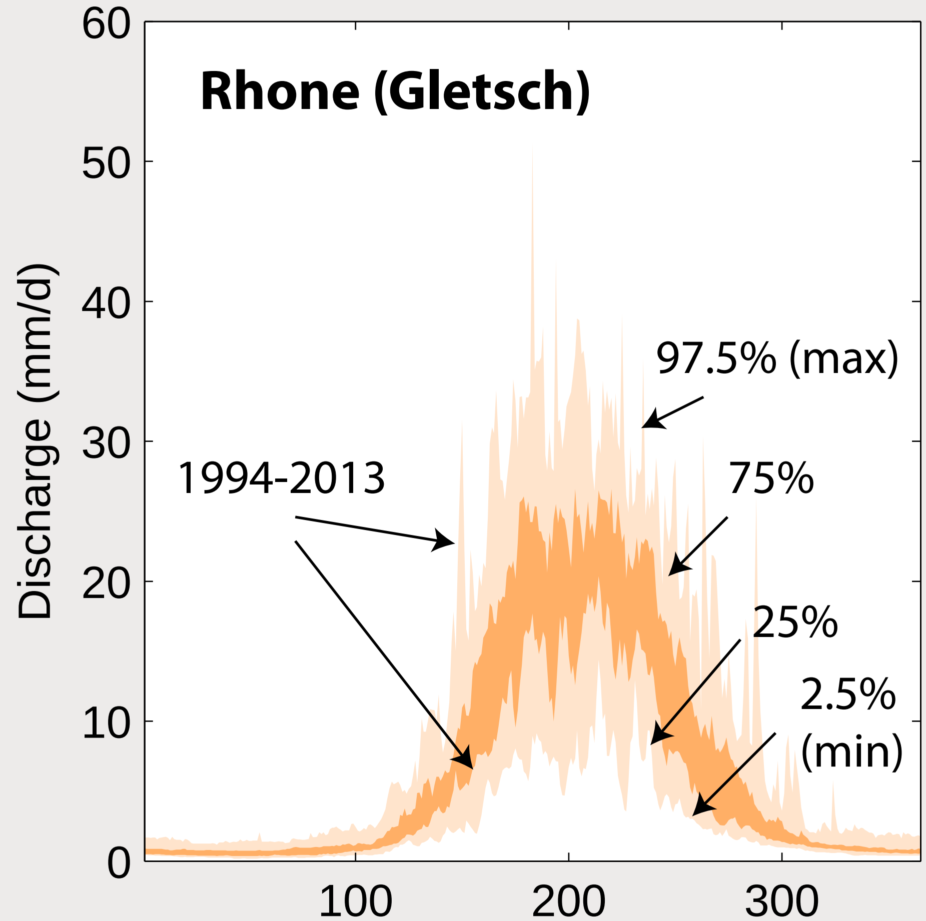
Catchment area	38.90 km^2
Mean elevation	2719 m
Glacier area	52%

http://www.hydrodaten.admin.ch/de/

Effect of glaciers: discharge @ Mosnang vs. Gletsch



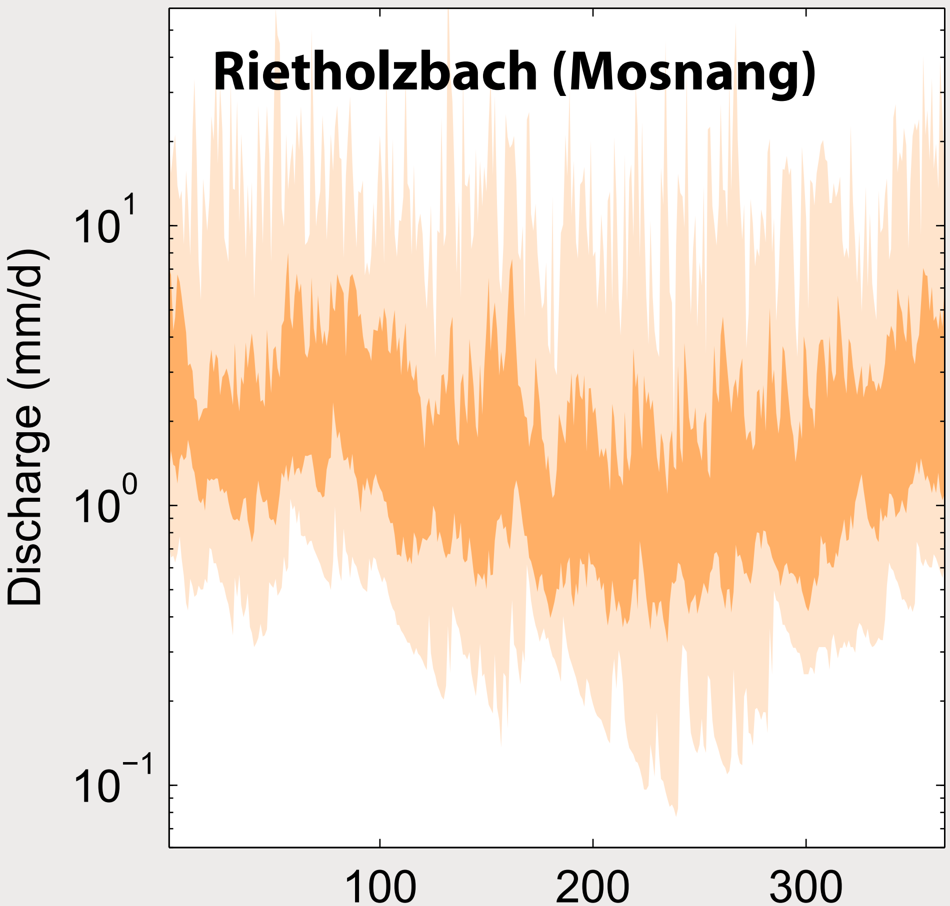
> No strong seasonality
> High discharge peaks
> Skewed distribution



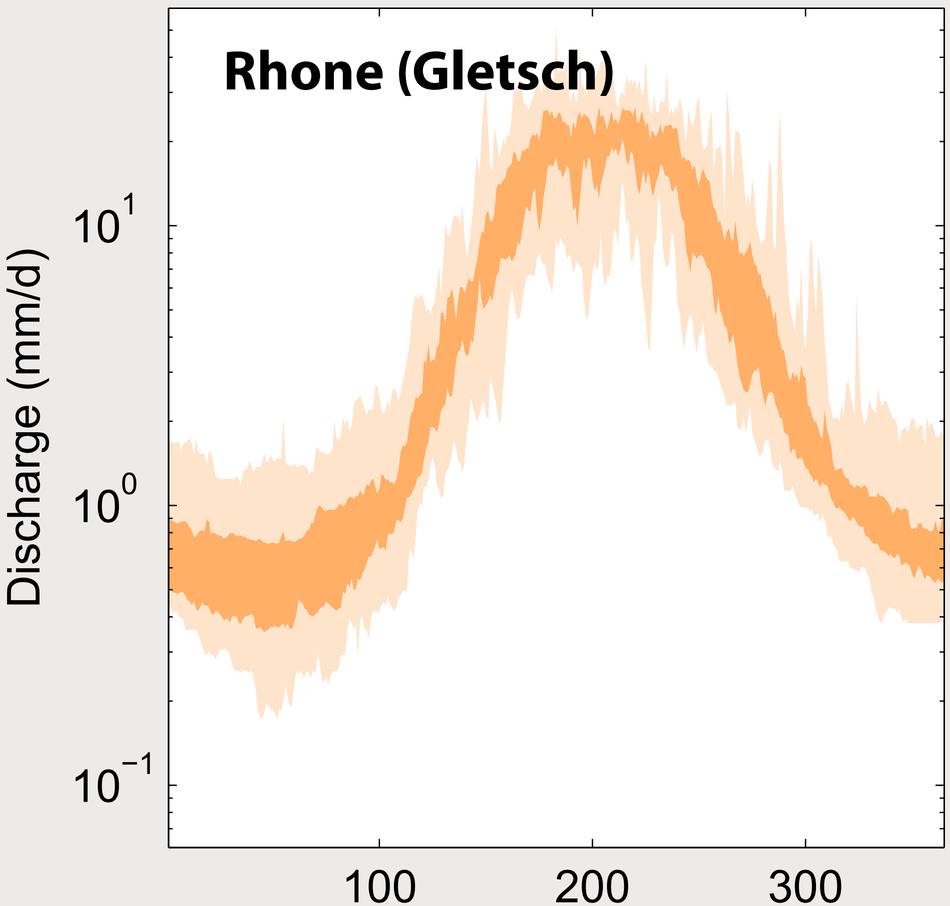
> Strong seasonality
> No high discharge peaks
> High summer discharge

http://www.hydrodaten.admin.ch/de/

Effect of glaciers: discharge @ Mosnang vs. Gletsch



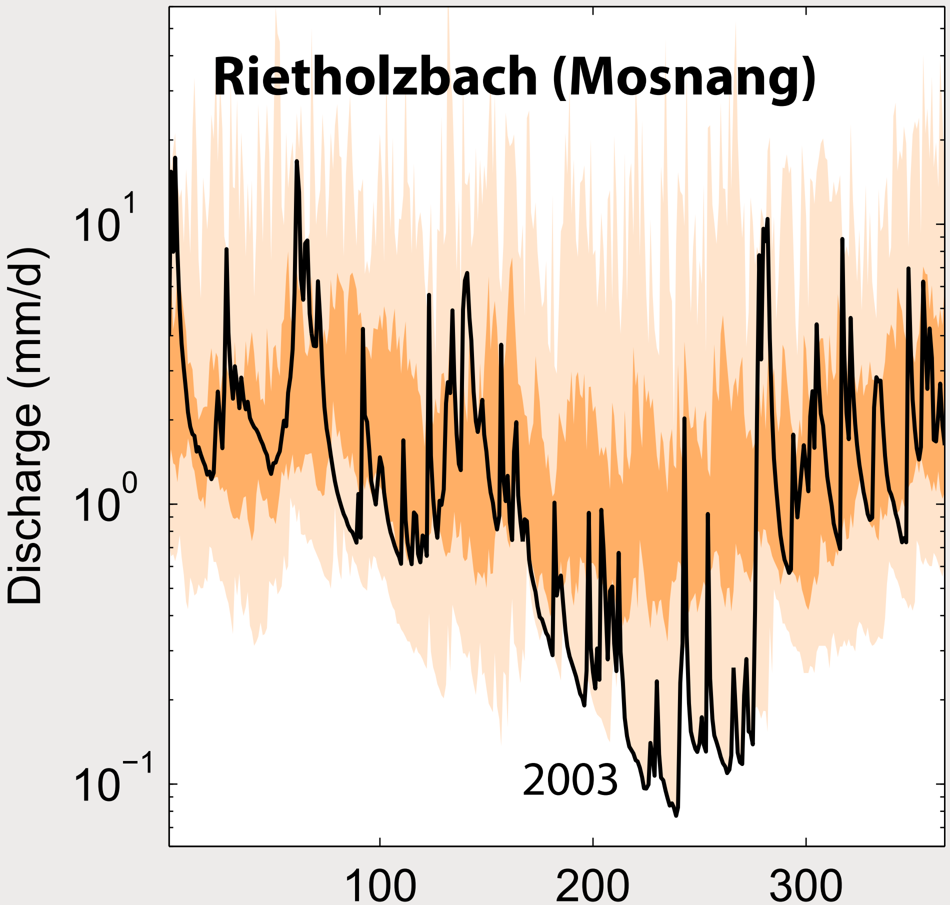
> High inter-annual variability
> Low seasonal variability
> Lowest discharge in summer



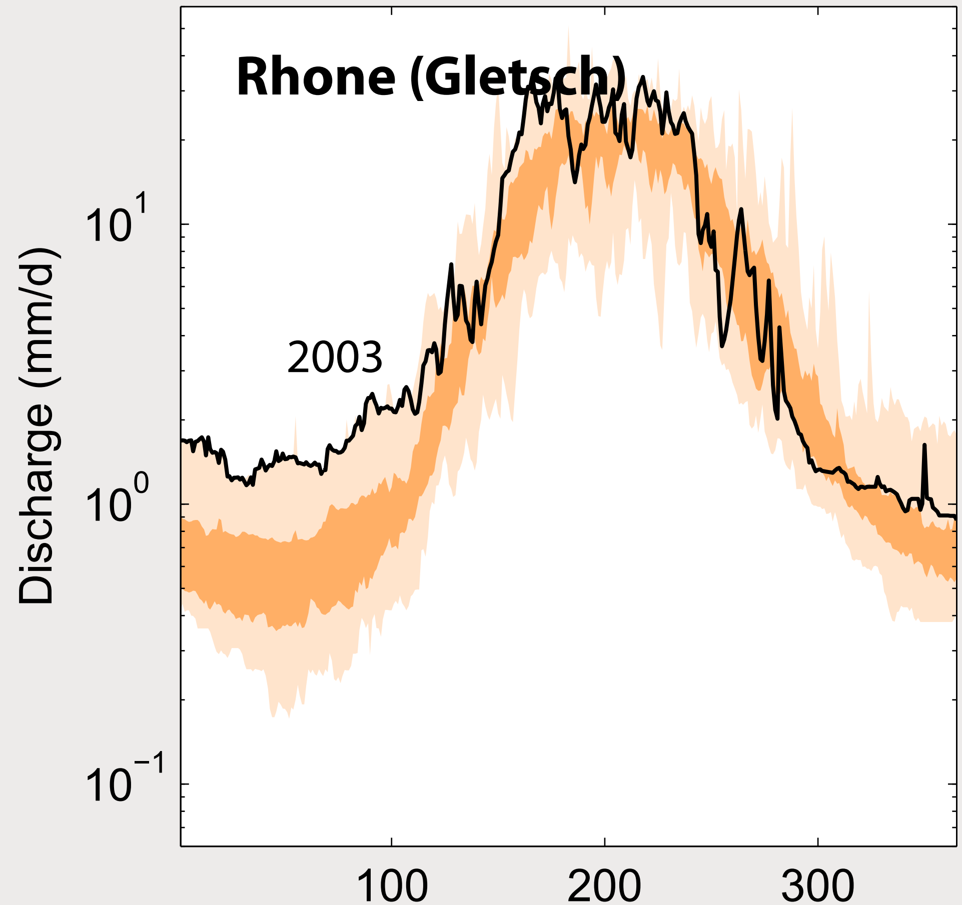
> Low inter-annual variability
> High seasonal variability

http://www.hydrodaten.admin.ch/de/

Effect of glaciers: discharge @ Mosnang vs. Gletsch



- Record low discharge during extreme (dry) summer of 2003
- Low storage due to drought



- Record high discharge during extreme (warm) summer of 2003
- High glacier melt rates

http://www.hydrodaten.admin.ch/de/

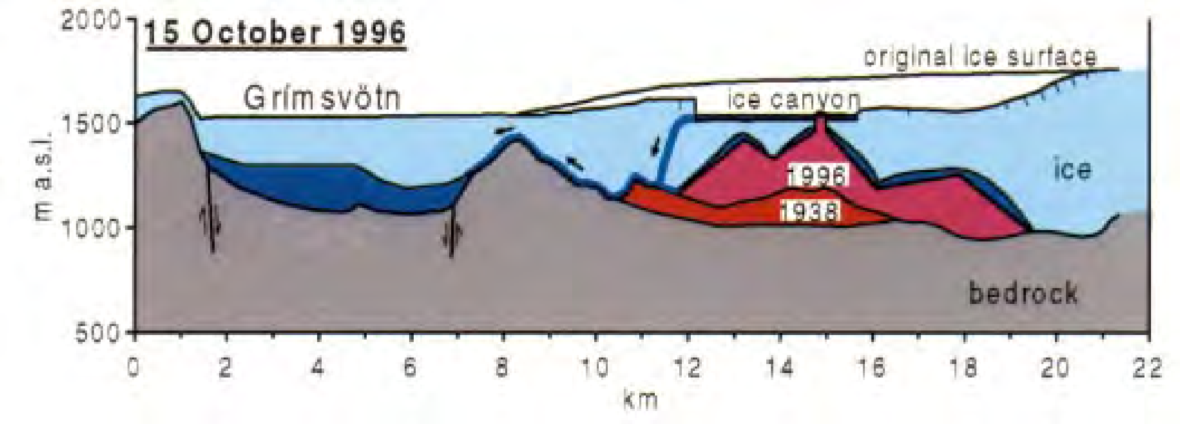
Rhone glacier during the hot summer of 2015

photo: Rhone glacier, July 2015 (Ryan Teuling)

Jökulhlaup (glacial outburst flood)

Name	Year	Peak ($m^3\ s^{-1}$)	Vol. (km^3)
Mýrdalsjökull	1755	>200,000	
Katla	1918	>300,000	3–8
Grímsvötn	1996	50,000	3
Eyjafjallajokull	2010	>2,000	
…	…	…	…

Mega-floods impact landscape formation. The 1918 flood extended the coastline by 5 km.




Kötlubjarg (transported boulder)


Eyjafjallajökull (2010)

Gudmundsson et al., 1997, Ice–volcano interaction of the 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. *Nature* **389**
Tomasson, 1996, The jokulhlaup froln Katla in 1918. *Ann. Glaciol.* **22**

Recent Jökulhlaup activity

Skaftá: a glacial outburst flood in progress

Warning

19.1.2014

Within the past 24 hours, the level of the Skaftá river at Sveinstindur has risen. Additionally electrical conductivity readings from the same location have increased.

These observations signify that a glacial outburstflood (jökulhlaup) is in progress. It is likely that the flood originated from the western Skaftá ice cauldron, which last drained in September 2012; however this is unconfirmed until visual observations are made.The discharge of Skaftá at Sveinstindur is presently 370 m^3/s.

A small jökulhlaup in Gígjukvísl

Glacier outburst flood

27.3.2014

A small jökulhlaup (glacier outburst flood) is now occurring in the river Gígjukvísl. The event originates from the subglacial lake Grímsvötn. The event is expected to be small, with maximum discharge on the order of magnitude 1000 cubic meters per second. The maximum of the flood is expected to be around the end of the week.

Conductivity measurements indicate a considerable increase of geothermal contribution to the water of the river. Simultaneously, the ice on the subglacial lake has lowered and seismic tremors have increased. These tremors are a consequence of the jökulhlaup and not indicative of volcanic activity.

Hydrogen sulphide is released from the floodwater as it drains from the Vatnajökull ice-cap. The gas is particularly potent at the river outlet at the ice margin, where concentrations may reach poisonous levels.

Otherwise, no threat is expected from this flood, which does not exceed high river discharge at summer. The road and bridge are safe.

http://en.vedur.is/about-imo/news/nr/2819
http://en.vedur.is/about-imo/news/nr/2859

Glacial lake outburst floods (GLOF)

A glacial lake outburst flood is a type of outburst flood occurring when water dammed by a glacier or a moraine is released. A water body that is dammed by the front of a glacier is called a marginal lake, and a water body that is capped by the glacier is called a subglacial lake.

GLOFs provide a major threat to people living in valleys of glacierized mountain regions such as the Himalayas and the Andes, but also in Switzerland where retreating glaciers create new lakes.

Mass balance field

$\dot{b}$ mass balance rate defined as net annual gain or loss at glacier surface with respect to vertical

Positive mass balance in accumulation zone: $\dot{b} > 0$

Zero mass balance at equilibrium line: $\dot{b} = 0$

Negative mass balance in ablation zone: $\dot{b} < 0$

Balance rate varies with altitude due to decreasing air temperature with altitude (lapse rate 6−7 K/km) and increasing precipitation. Balance gradient is defined as:

$$\beta = \frac{\mathrm{d}\dot{b}}{\mathrm{d}z}$$

Values for balance gradient range from 0.003 to 0.008 mwe y^{-1} m^{-1}

Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

A minimal glacier model (1)

Simplest glacier has uniform width, constant balance gradient, and rests on bed with constant slope. Bed elevation is given by:

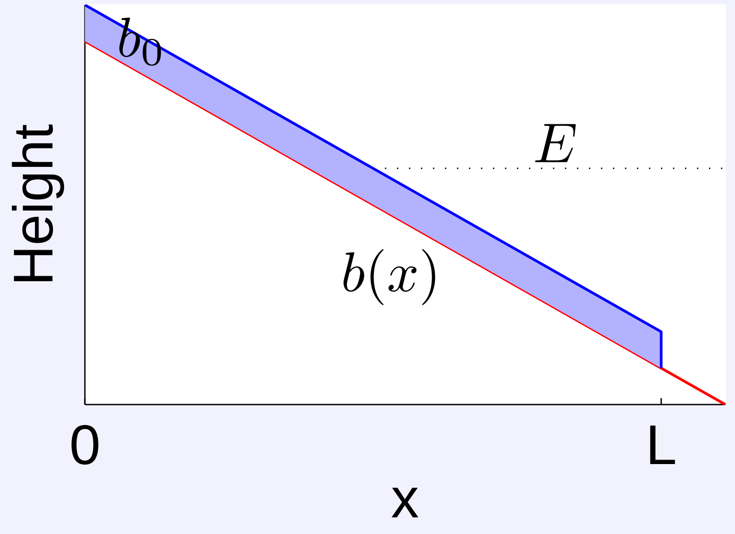
$$b(x) = b_0 - sx$$

Assuming a linear balance rate:

$$\dot{b} = \beta(z - E)$$

In equilibrium, total mass budget is zero:

$$\int_0^L \dot{b} \, \mathrm{d}x = 0$$



Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

A minimal glacier model (2)

Zero mass budget:

$$\int_0^L \dot{b}\,\mathrm{d}x = \beta \int_0^L (H + b_0 - sx - E)\mathrm{d}x = 0$$

Solving for glacier length *L:*

$$L = \frac{2(H_m + b_0 - E)}{s}$$

Where H_m is the mean ice thickness:

$$H_m = \frac{1}{L}\int_0^L H\mathrm{d}x$$

Relating H_m to the slope of the bed requires assuming perfect plasticity in a global sense:

$$\rho g s H_m = \tau_0$$

Eleminating H_m then leads to:

$$L = \frac{2}{s}\left(\frac{\tau_0}{\rho g s} + b_0 - E\right)$$

Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

First−order climate sensitivity of glaciers

The sensitivity of L to changes in elevation of the equilibrium line due to climate change is given by:

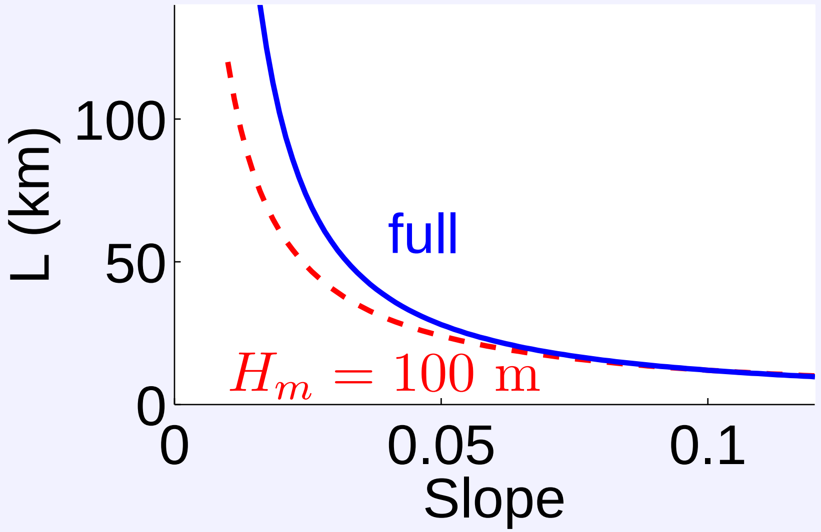
$$\frac{\mathrm{d}L}{\mathrm{d}E} = -\frac{2}{s}$$

This shows that glaciers on smaller bed slopes are more sensitive in an absolute sense. The relative sensitivity shows the opposite behavior.

The relative sensitivity is given by:

$$\frac{1}{L}\frac{\mathrm{d}L}{\mathrm{d}E} = -\left(\frac{\tau_0}{\rho g s} + b_0 - E\right)^{-1}$$

With $b_0 - E = 500$ m and $\tau_0/\rho g = 10$ m, the relation between length and slope is:



Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

First−order climate sensitivity of glaciers

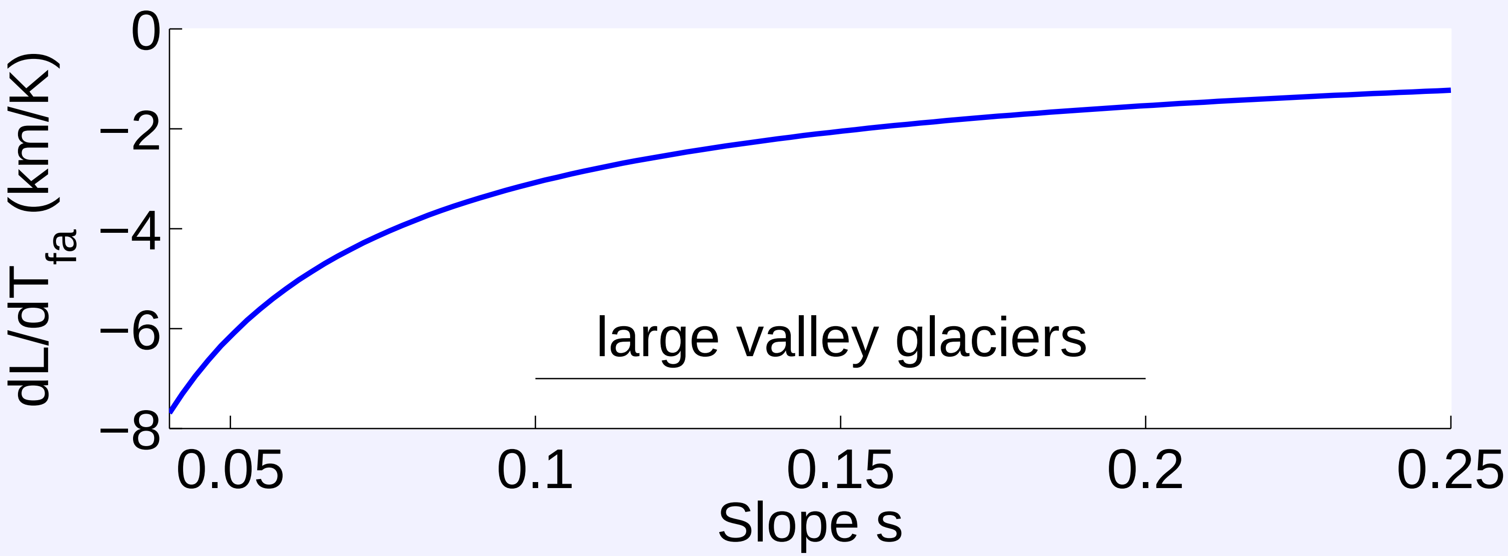
For an estimate of the temperature dependency of glacier length, it can be assumed that the equilibrium line follows an isotherm.

With the temperature lapse rate γ it follows that:

$$\frac{\mathrm{d}E}{\mathrm{d}T_{fa}} = -\frac{1}{\gamma_a}$$

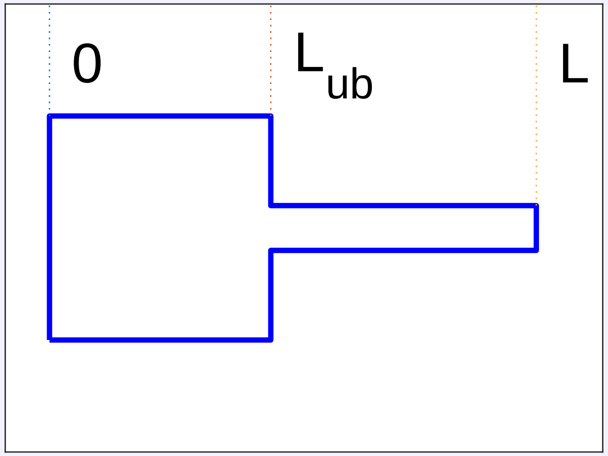
Using dL/dE = −2/s it follows that:

$$\frac{\mathrm{d}L}{\mathrm{d}T_{fa}} = \frac{2}{\gamma_a s}$$



Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

More complex geometry



Alpine glaciers typically have wider accumulation basins than tongues. This affects the sensitivity of glacier length to climate change. A simple geometry is given by ξ, the ratio between tongue width and the basin width.

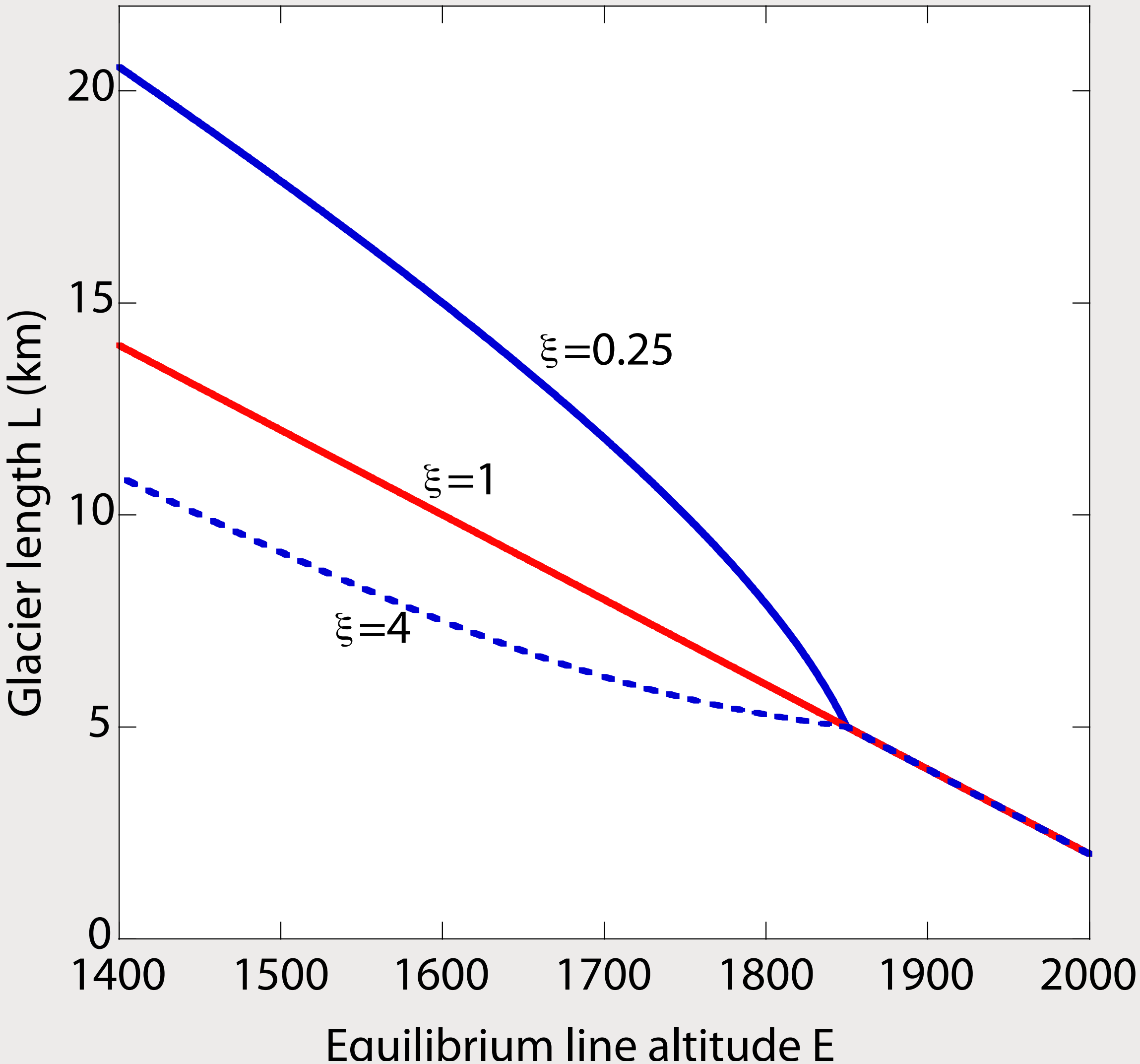
With a uniform ice thickness H_m, and

$E_r = E - b_0 - H_m$, the length L is:

$$L = -\frac{1}{s}\left(E_r \pm \sqrt{E_r^2 - 2s\frac{1-\xi}{\xi}(E_r L_{ub} + \frac{1}{2}sL_{ub}^2)}\right)$$

Minimal glacier models, J. Oerlemans, Utrecht University, 2008.

More complex geometry



In glaciers with more complex geometry, the climate sensitivity depends on the geometry as prescribed by ξ.

Parameter values for the plot are:

b_0 = 2000 m
s = 0.1
H_m = 100 m
L_{ub} = 5000 m

Minimal glacier models, J. Oerlemans, Utrecht University, 2008.