Snow hydrology

Walter Immerzeel

Emmy Stigter

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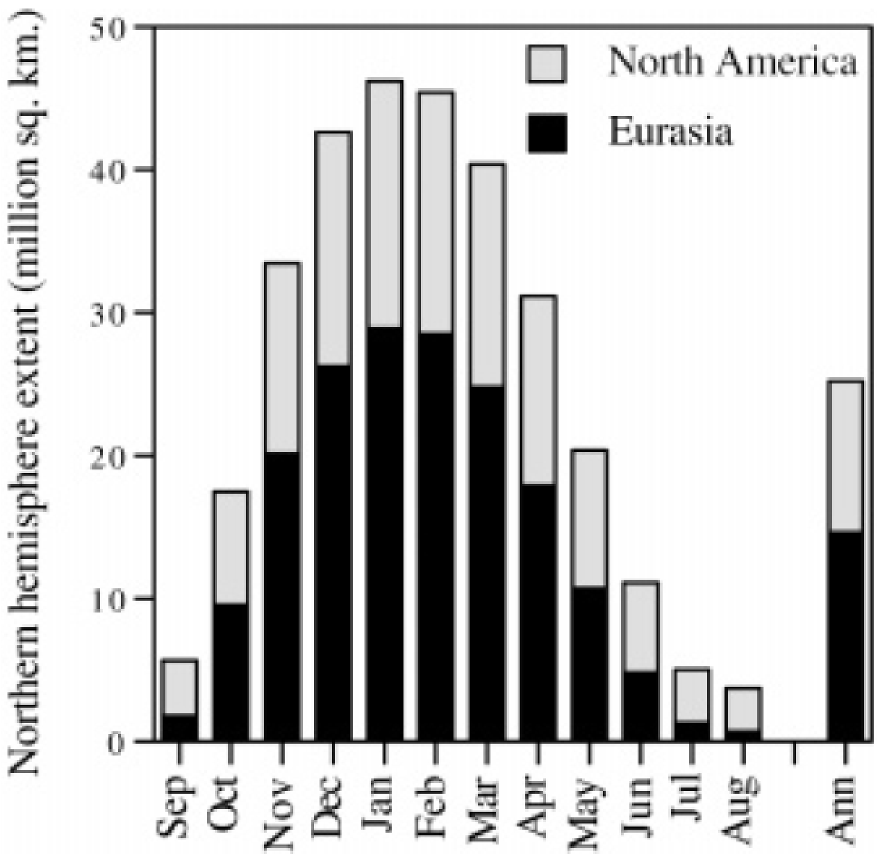
Hydrology, Climate Change and Cryosphere

Topics

- Importance of snow
- Snow processes
- Snowmelt phases and energy balance
- Water movement through snow
- Field measurements
- Modelling and remote sensing

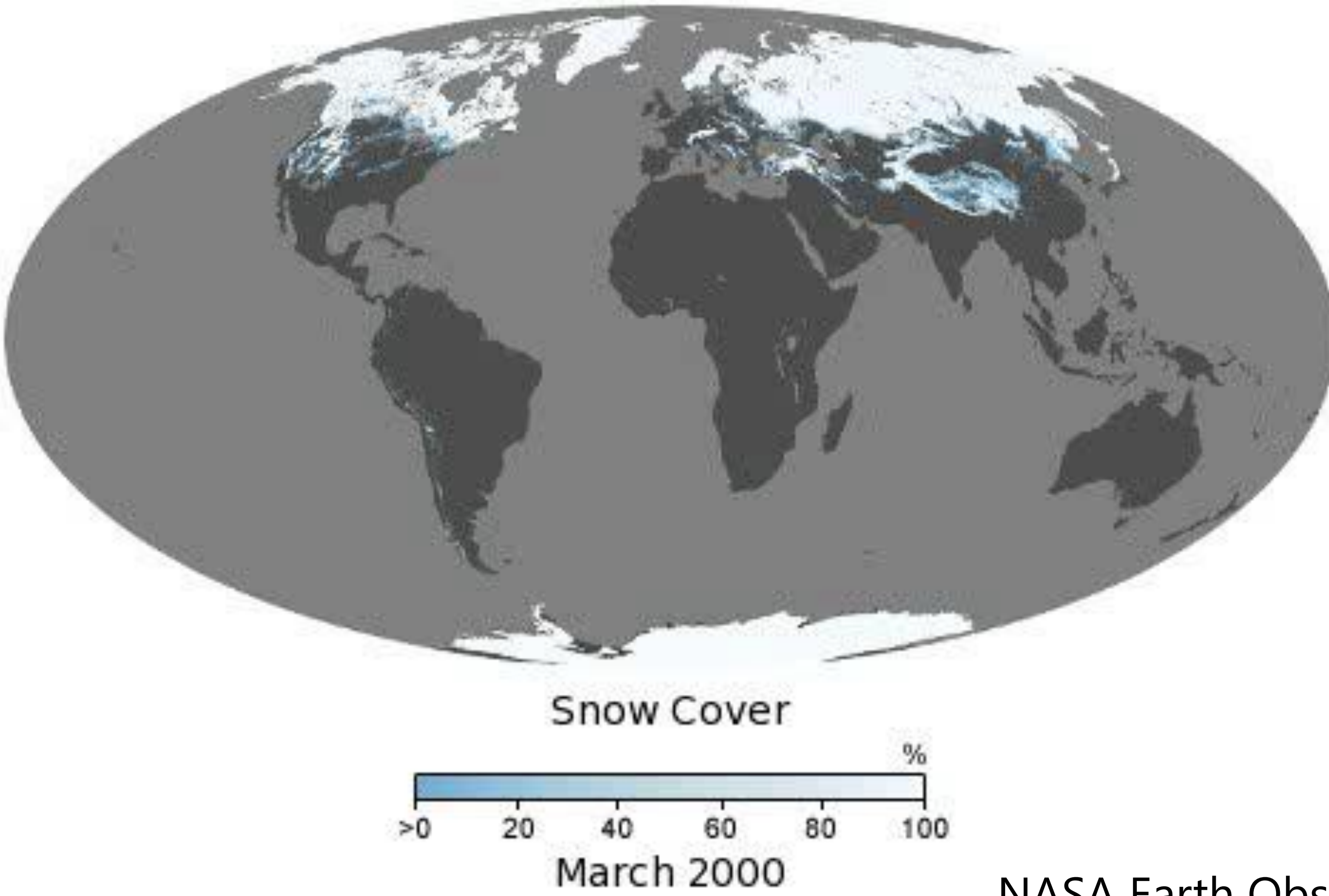
Global snow cover

Mean monthly SE (1972-1999)



Robinson and Frei, 2000

Global snow cover



NASA Earth Observatory

Global snow cover

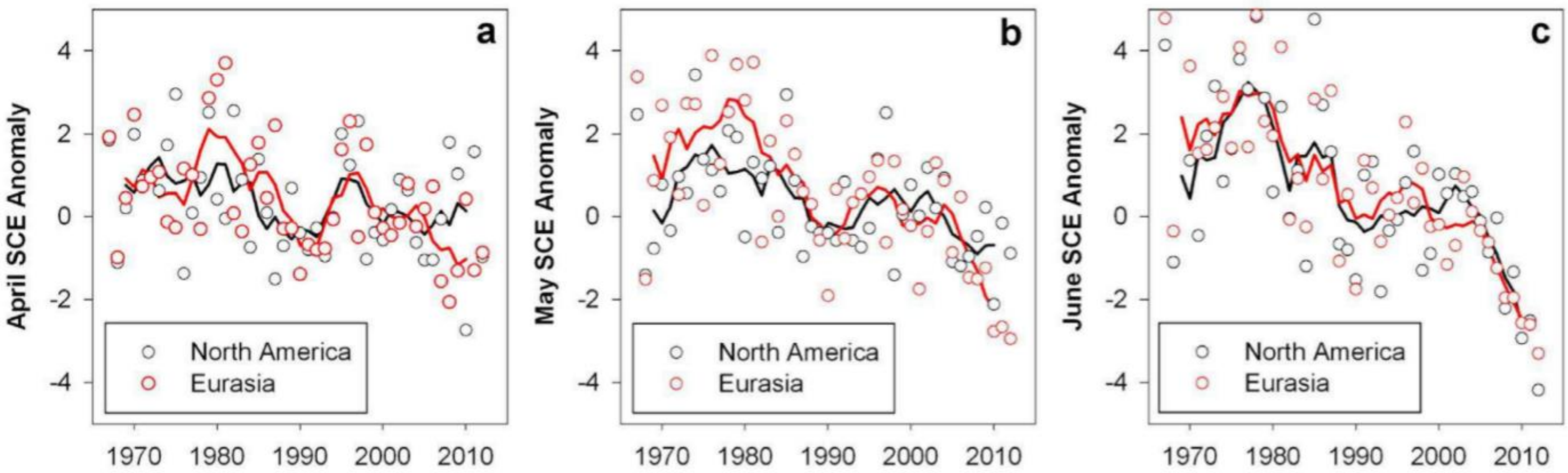


Figure 1. Snow cover extent (SCE) anomaly time series (with respect to 1988–2007) from the NOAA snow chart CDR for (a) April, (b) May, and (c) June. Solid line denotes 5-yr running mean.

Derksen and Brown, 2012

Importance of snow

- Hydrology
  - Domestic use
  - Floods
  - Hydro power production
  - Irrigation
- Climate
  - High albedo (affects energy balance)
- Avalanches

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Physical snow properties

Property	Fresh snow	Settled snow
Density ($kg\ m^{-3}$)		
Albedo (-)		
Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)		

Physical snow properties

Property	Fresh snow	Settled snow
Density (kg m^{-3})	20-150	
Albedo (-)		
Thermal conductivity (W m^{-1} $°C^{-1}$)		

Physical snow properties

Property	Fresh snow	Settled snow
Density (kg m^{-3})	20-150	250-550
Albedo (-)		
Thermal conductivity (W m^{-1} $°C^{-1}$)		

Physical snow properties

Property	Fresh snow	Settled snow
Density (kg m^{-3})	20-150	250-550
Albedo (-)	0.8-0.9	
Thermal conductivity (W m^{-1} °C^{-1})		

Physical snow properties

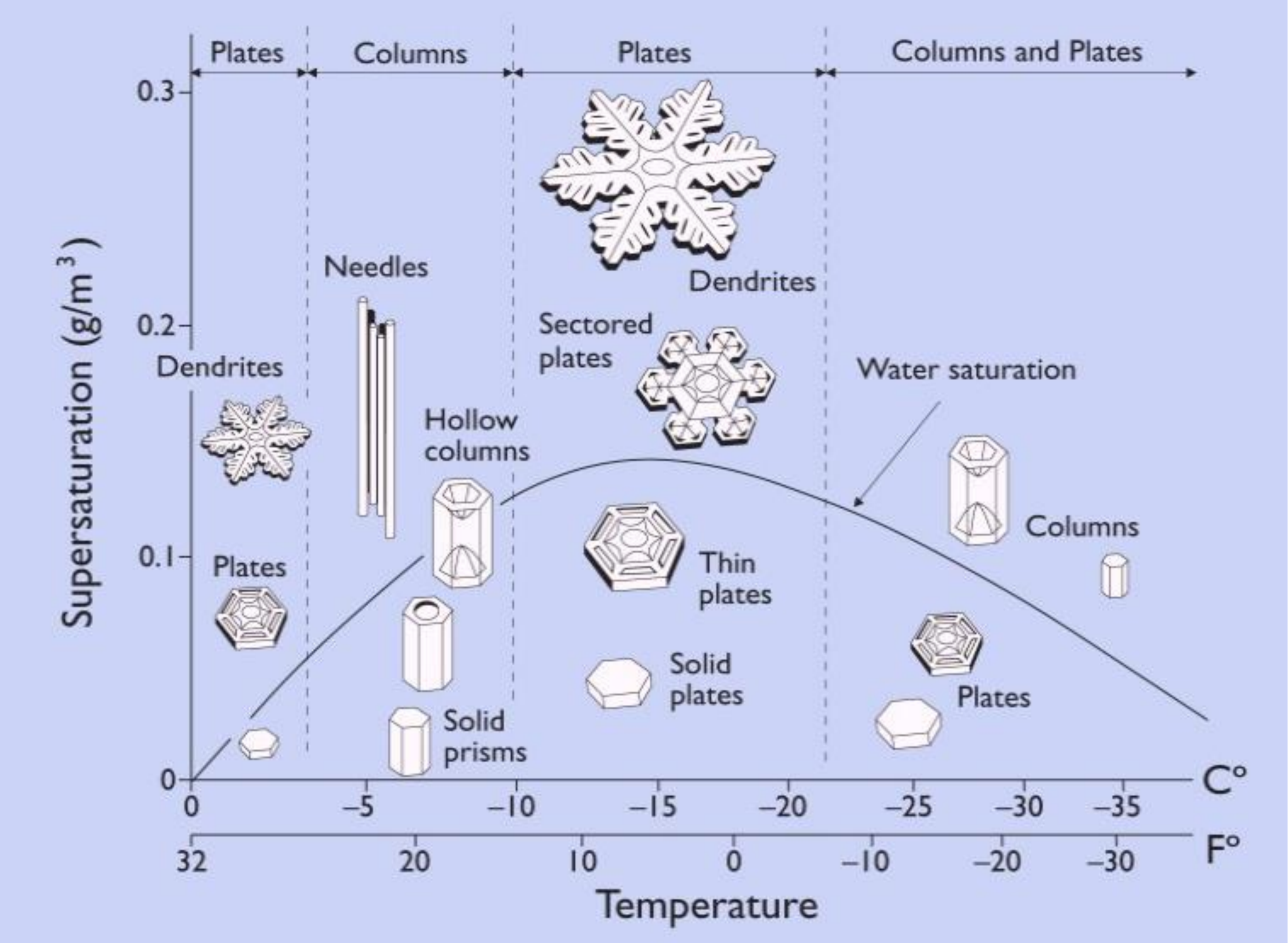
Property	Fresh snow	Settled snow
Density (kg m^{-3})	20-150	250-550
Albedo (-)	0.8-0.9	0.4-0.6
Thermal conductivity (W m^{-1} $°C^{-1}$)		

Physical snow properties

Property	Fresh snow	Settled snow
Density (kg m^{-3})	20-150	250-550
Albedo (-)	0.8-0.9	0.4-0.6
Thermal conductivity (W m^{-1} $°C^{-1}$)	0.03-0.06	0.1-0.7

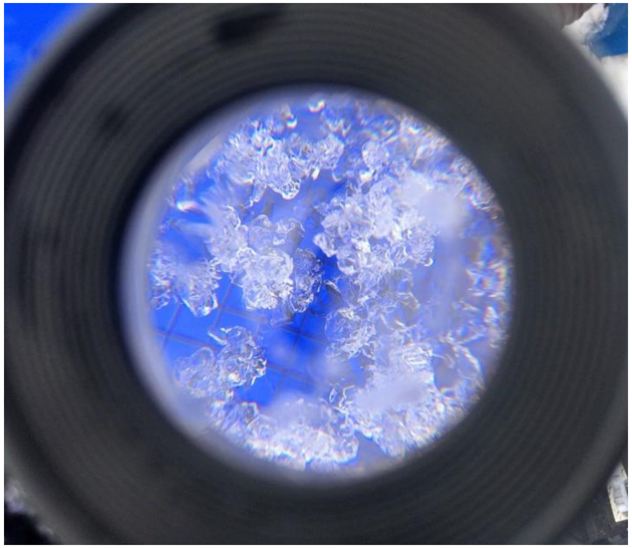
It all starts with snowfall

It all starts with snowfall



Snow metamorphism

Permanent transition – crystals are formed that cannot be found in the atmosphere



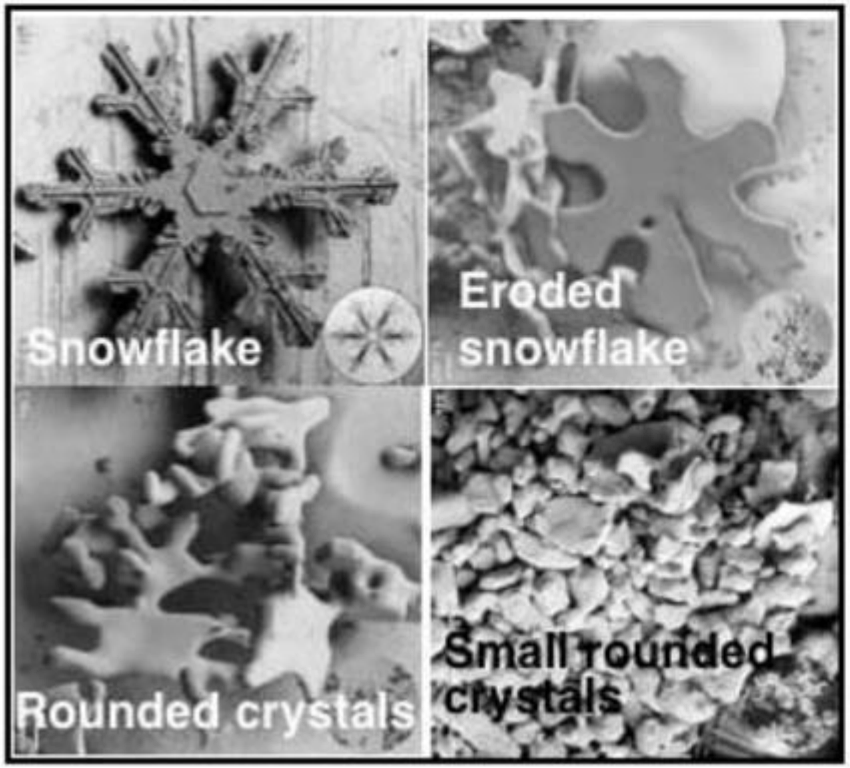
Snow metamorphism

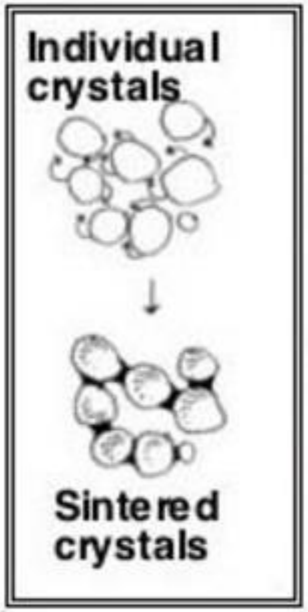
Snow metamorphism

- Gravitational settling
- Destructive & Constructive metamorphism
- Melt metamorphism

Snow metamorphism

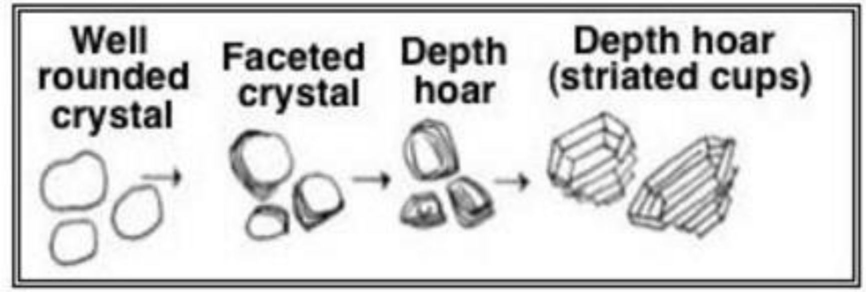
Destructive metamorphism





Snow metamorphism

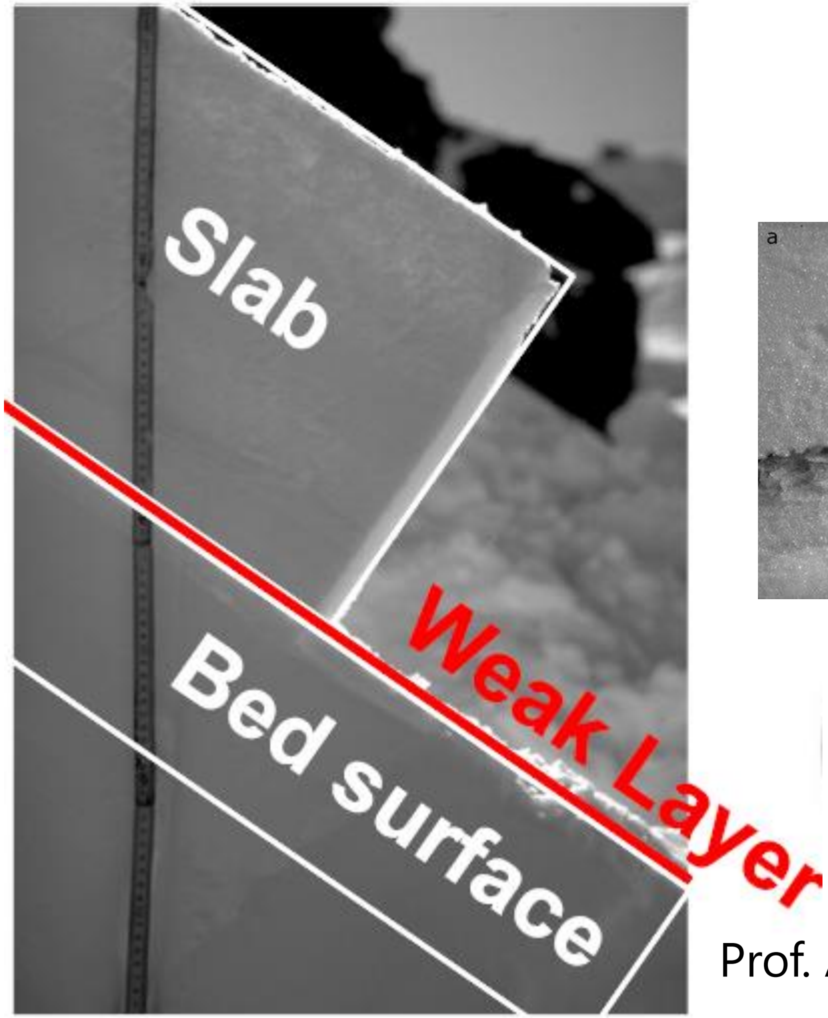
Constructive metamorphism



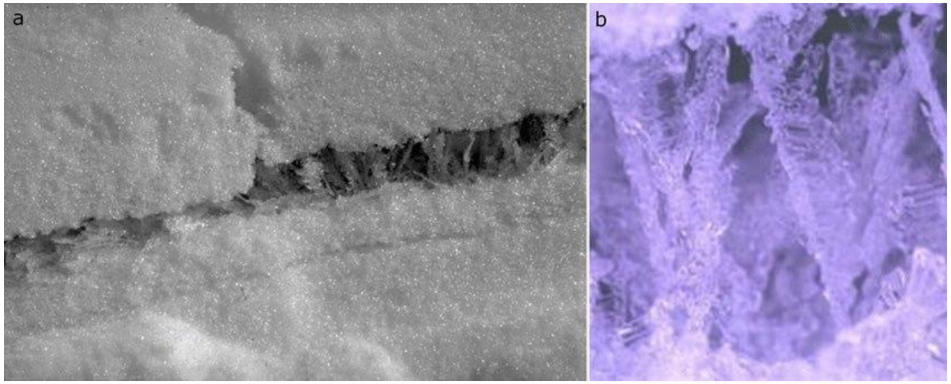
Snow metamorphism

Prof. A. Prokop

Snow metamorphism

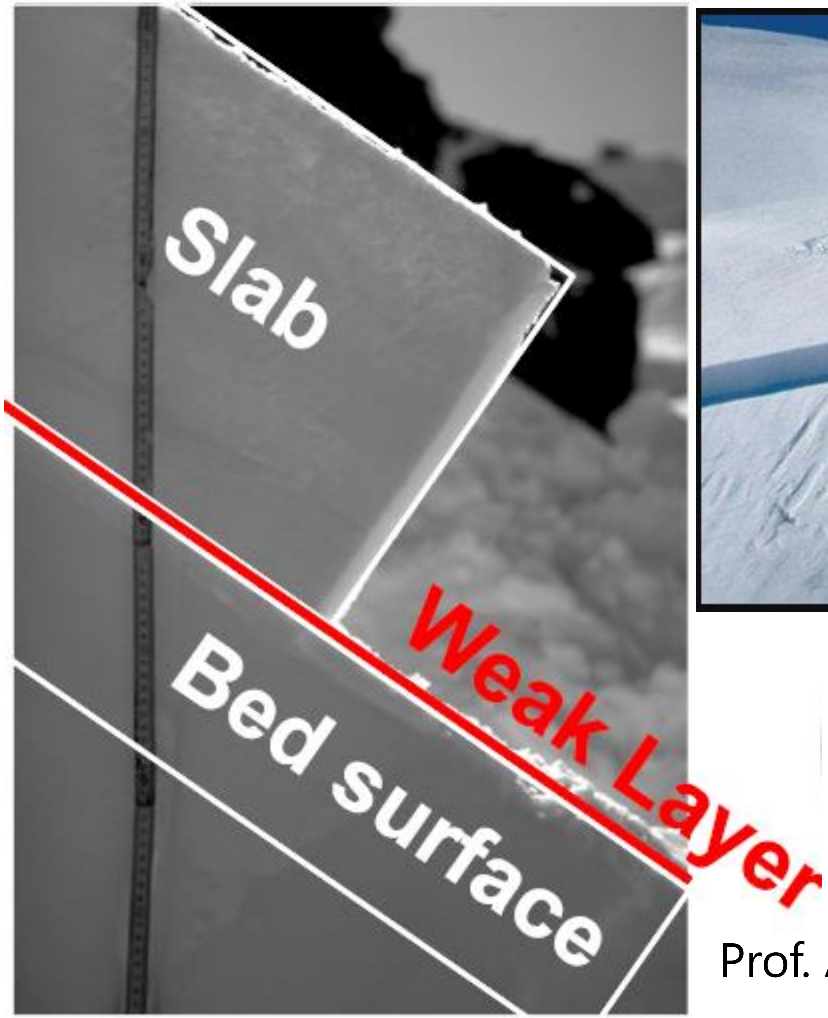


Prof. A. Prokop



SLAB Lab, EPFL

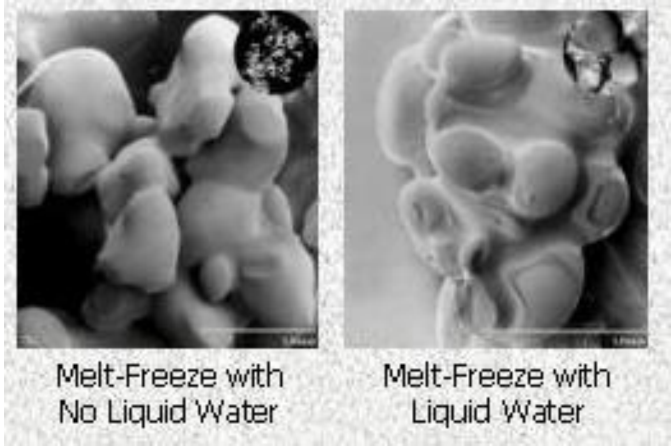
Snow metamorphism

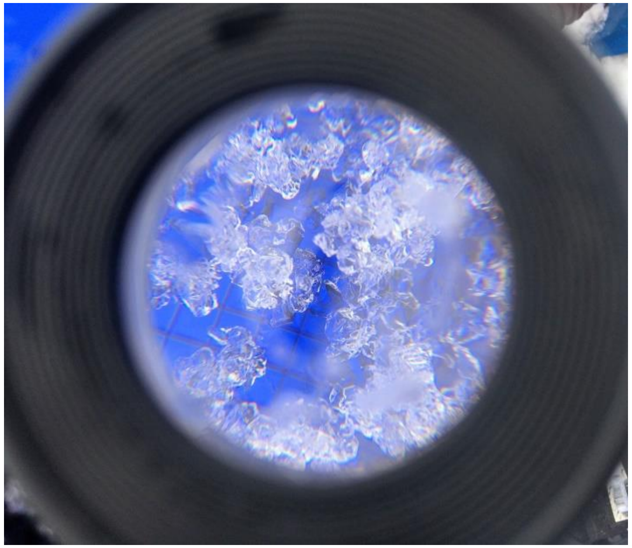


Prof. A. Prokop

Snow metamorphism

Melt-freeze metamorphism





Snow metamorphism

Associated changes that occur in the snowpack

- Density
- Albedo
- Thermal conductivity
- Porosity
- Water content

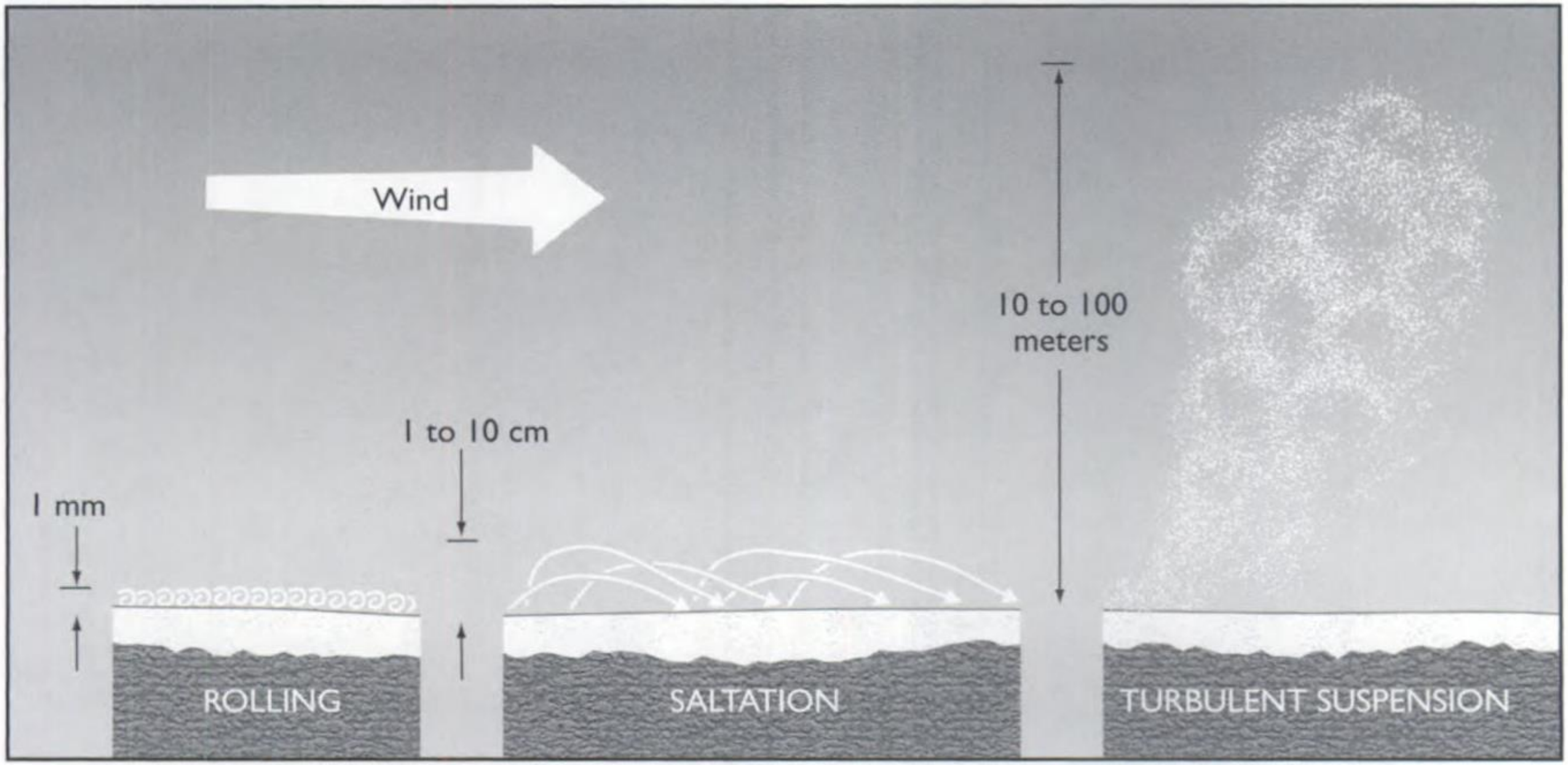
Redistribution by wind

Redistribution by wind

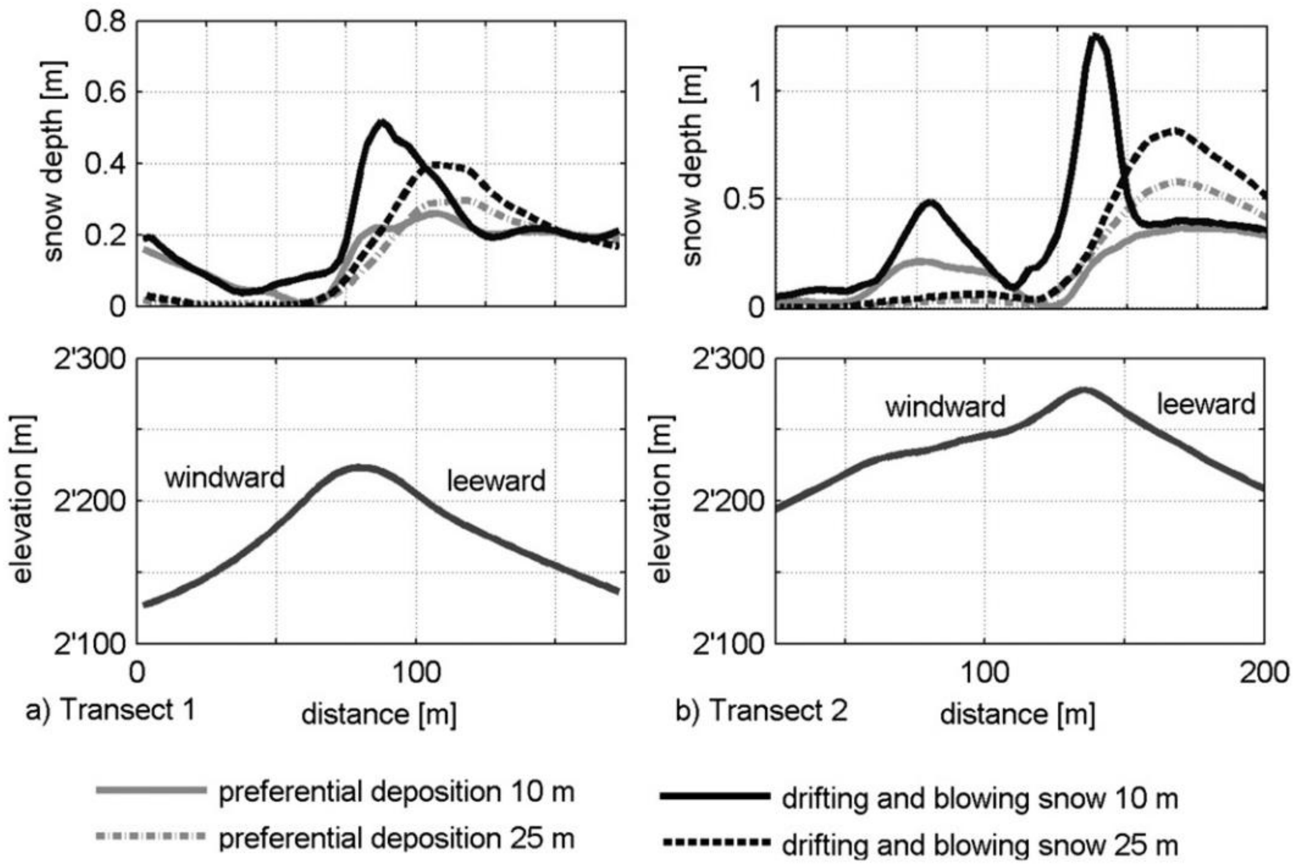
Redistribution by wind

Snow transport

- creep -saltation - suspension



Redistribution by wind



Mott and Lehning, 2010

Redistribution by wind

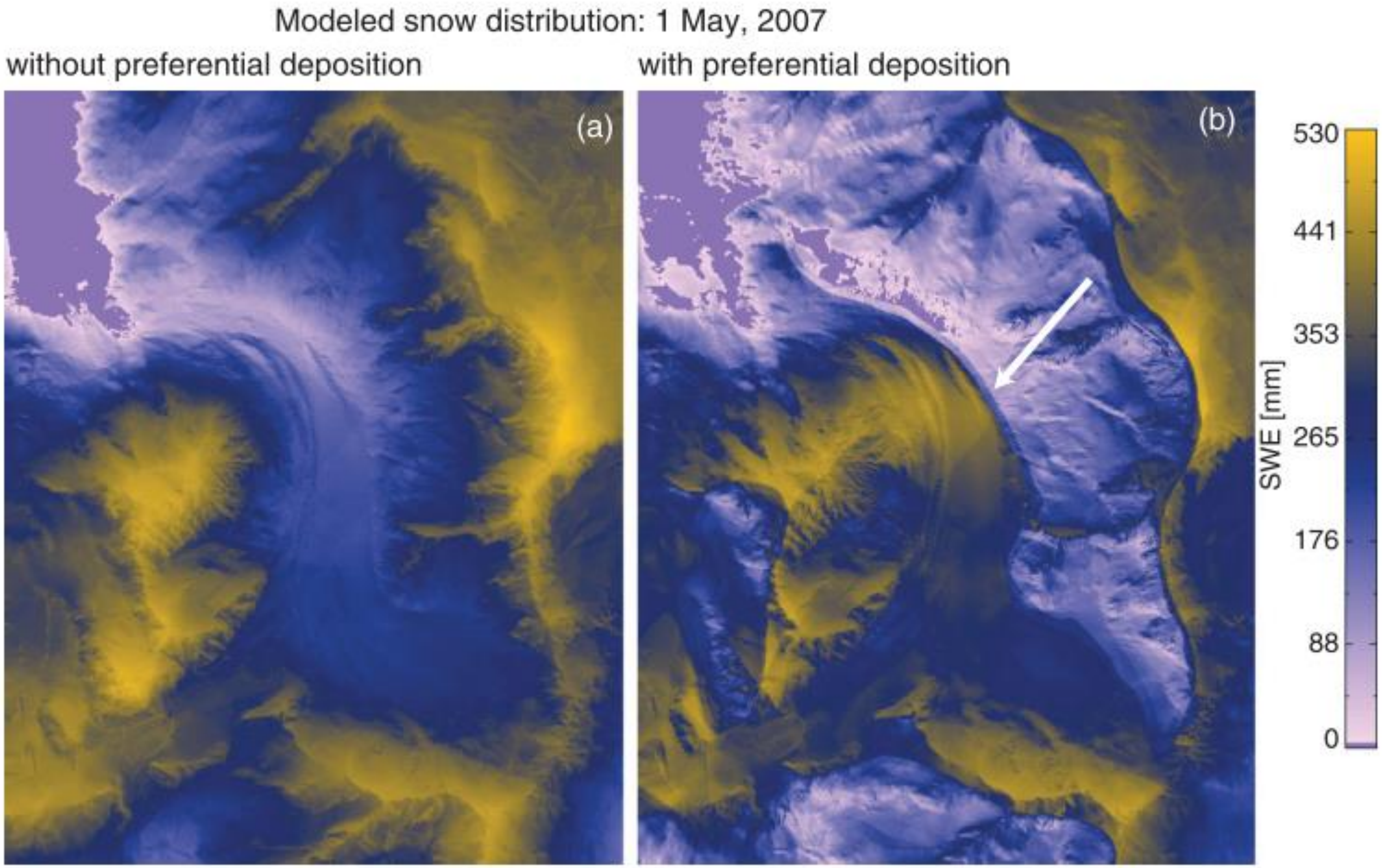


Figure 6. SnowDEM model runs without preferential deposition (a) and with preferential deposition (b)

Dadic et al ., 2010

Redistribution by wind/avalanching

Svalbardposten.no

Redistribution by wind/avalanching

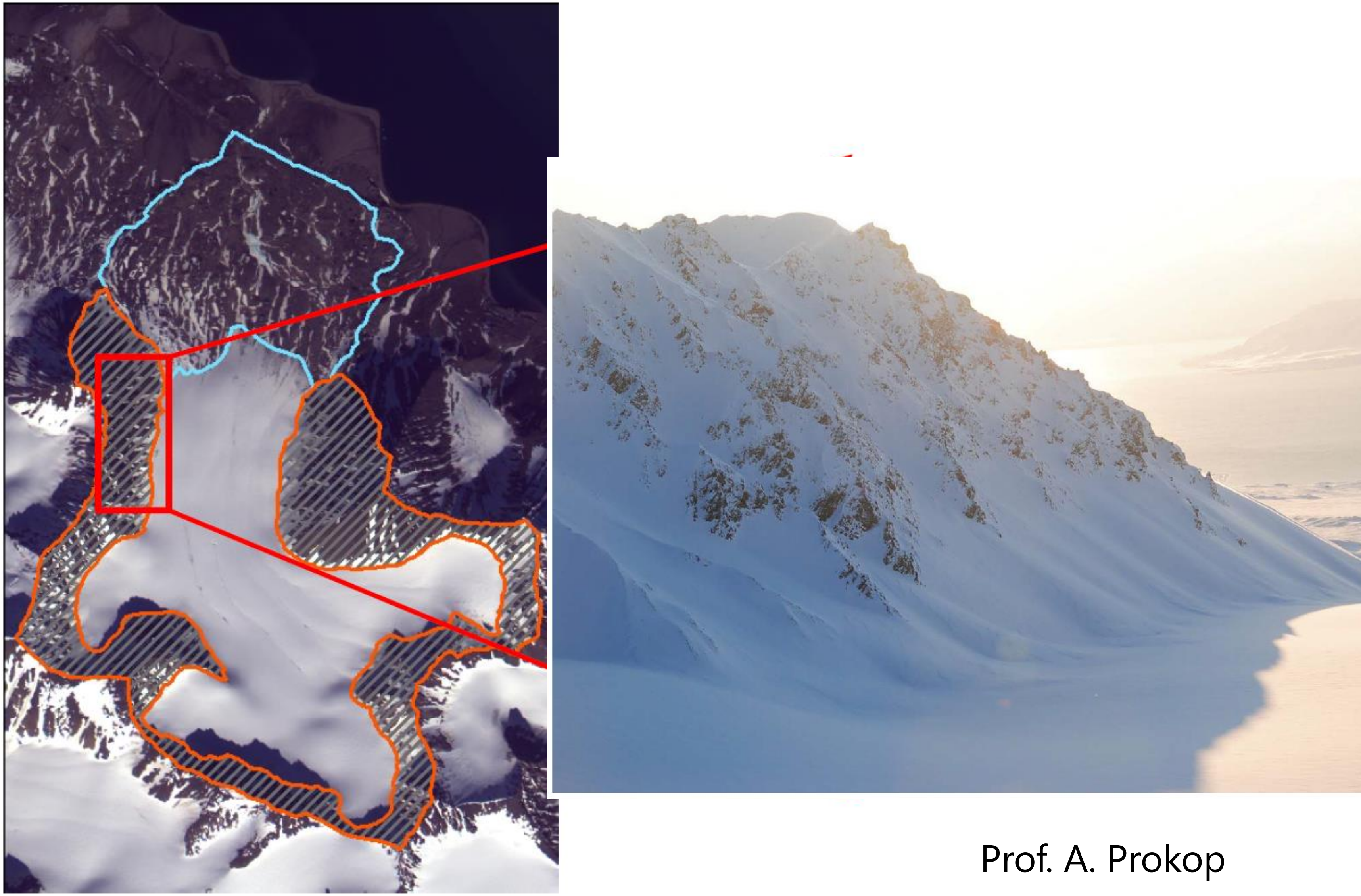
Svalbardposten.no

Redistribution by avalanching

Transport of snow to lower elevations

J. Steiner

Redistribution by avalanching



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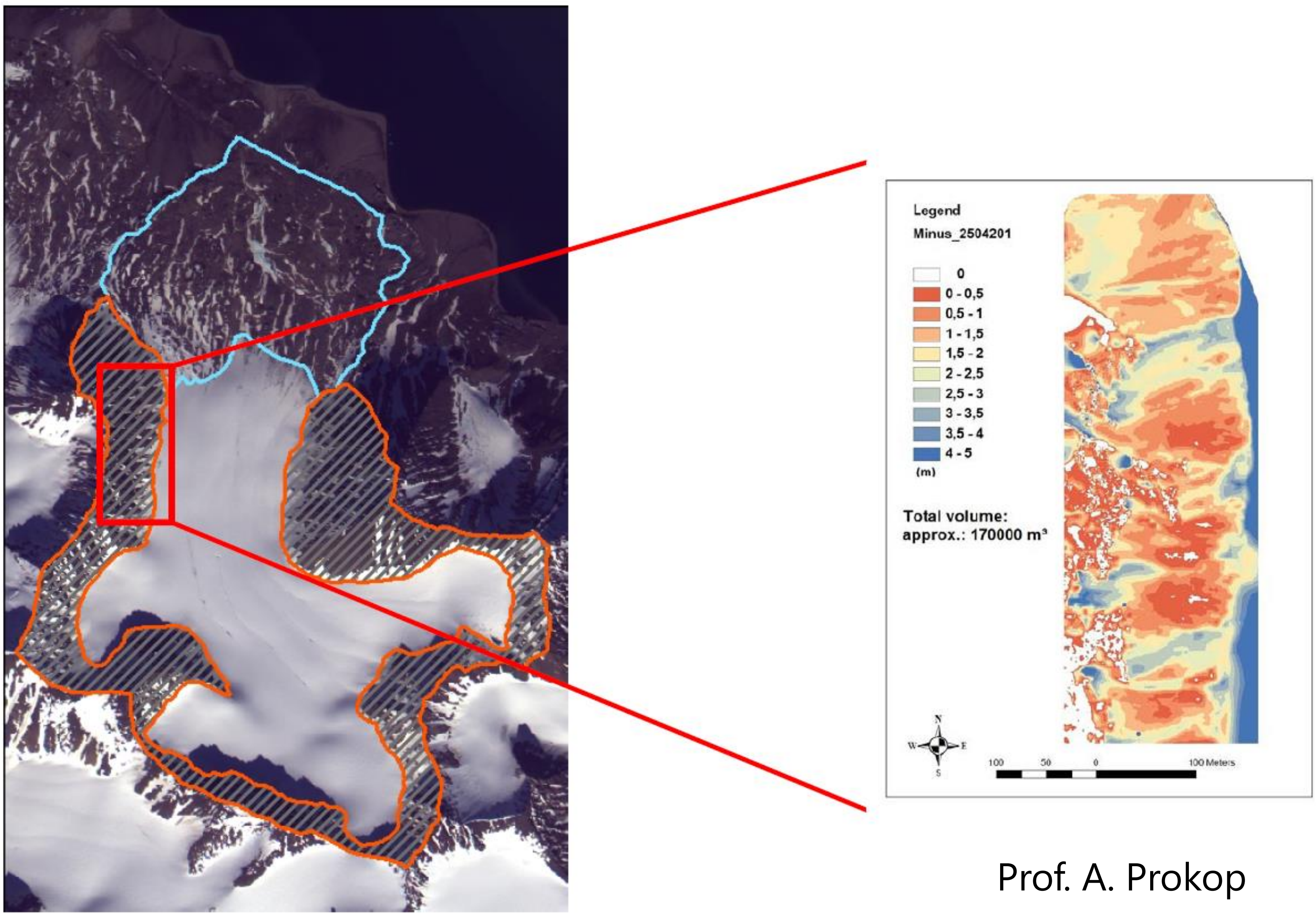
Redistribution by avalanching



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How snow disappears without melting

Sublimation

- Loss of water to the atmosphere due to direct transition of snow to water vapour
- Driven by wind speed and vapour gradient between snow surface and atmosphere

$$\boxed{\mathrm{LE} = \lambda\, \rho_a\, C_e\, u\, (e_a - e_s)}$$

The Importance of Snow Sublimation on a Himalayan Glacier

Emmy E. Stigter[1*], Maxime Litt[1,2], Jakob F. Steiner[1], Pleun N. J. Bonekamp[1], Joseph M. Shea[2,3,4], Marc F. P. Bierkens[1,5] and Walter W. Immerzeel[1]

[1]Department of Physical Geography, Utrecht University, Utrecht, Netherlands
[2]International Centre for Integrated Mountain Development, Kathmandu, Nepal
[3]Centre for Hydrology, University of Saskatchewan, Canmore, AB, Canada
[4]University of Northern British Columbia, Prince George, BC, Canada
[5]Deltares, Utrecht, Netherlands

Sublimation

- Loss of water to the atmosphere due to direct transition of snow to water vapour

- Driven by wind speed and vapour gradient between snow surface and atmosphere

$$\boxed{\mathrm{LE} = \lambda \rho_a C_e u (e_a - e_s)}$$

$$\boxed{e_a = e_{sat} RH}$$

$$\boxed{e_s = 0.6108 e^{\frac{17.27 T_s}{T_s + 237.3}}}$$

Sublimation

Where:

ρ_a = air density (kg m^{-3})

c_a = specific heat of dry air (J kg^{-1} K^{-1})

u = wind speed at elevation z (m s^{-1})

T_a = air temperature at elevation z (°C)

T_s = snow temperature (°C)

λ = latent heat of vaporization or sublimation (J kg^{-1})

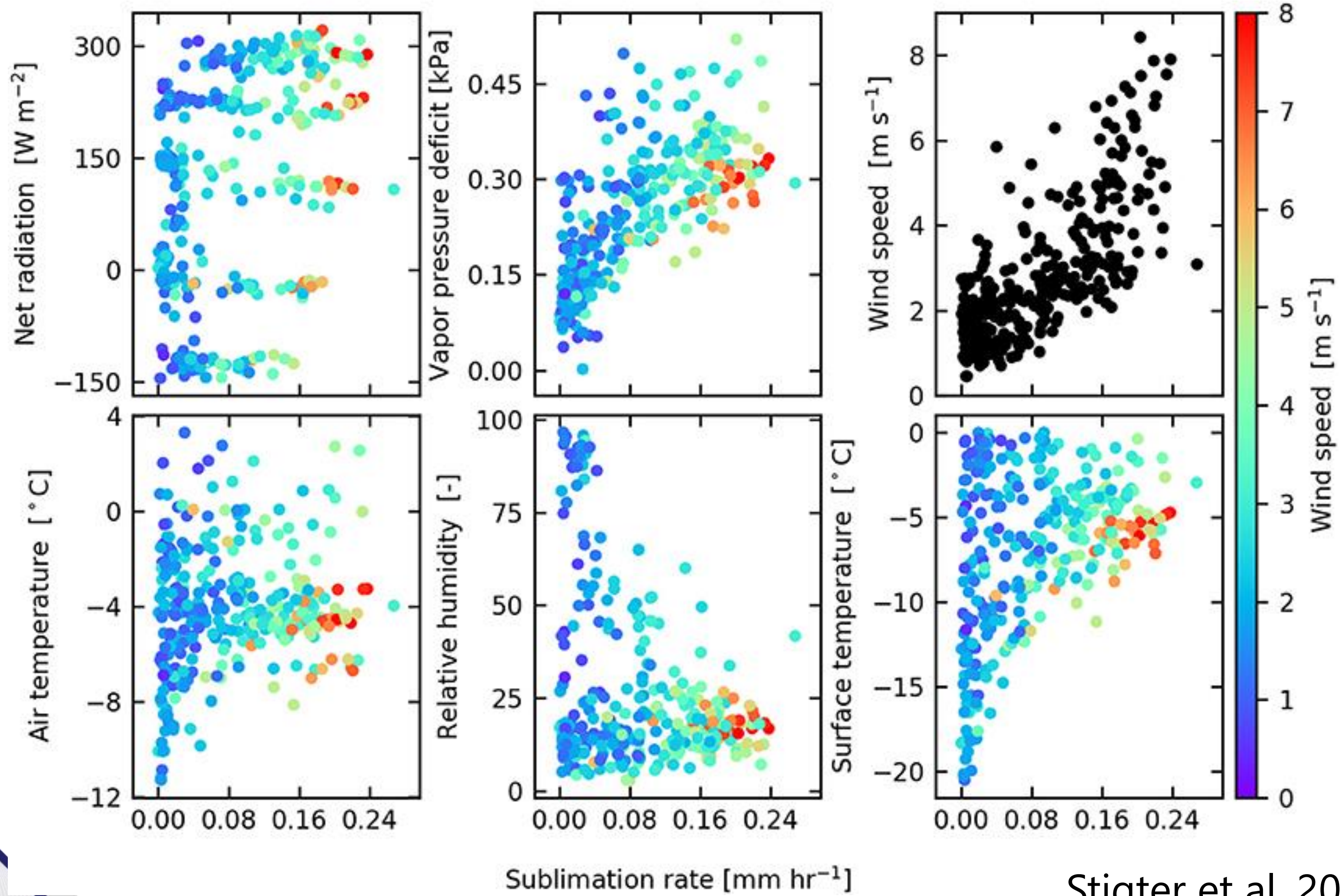
RH = relative humidity (-)

C_e = bulk transfer coefficient for vapour exchange (-)

e_a = atmospheric vapor pressure at height z (Pa)

e_s = vapor pressure at the snowpack surface (Pa)

Sublimation

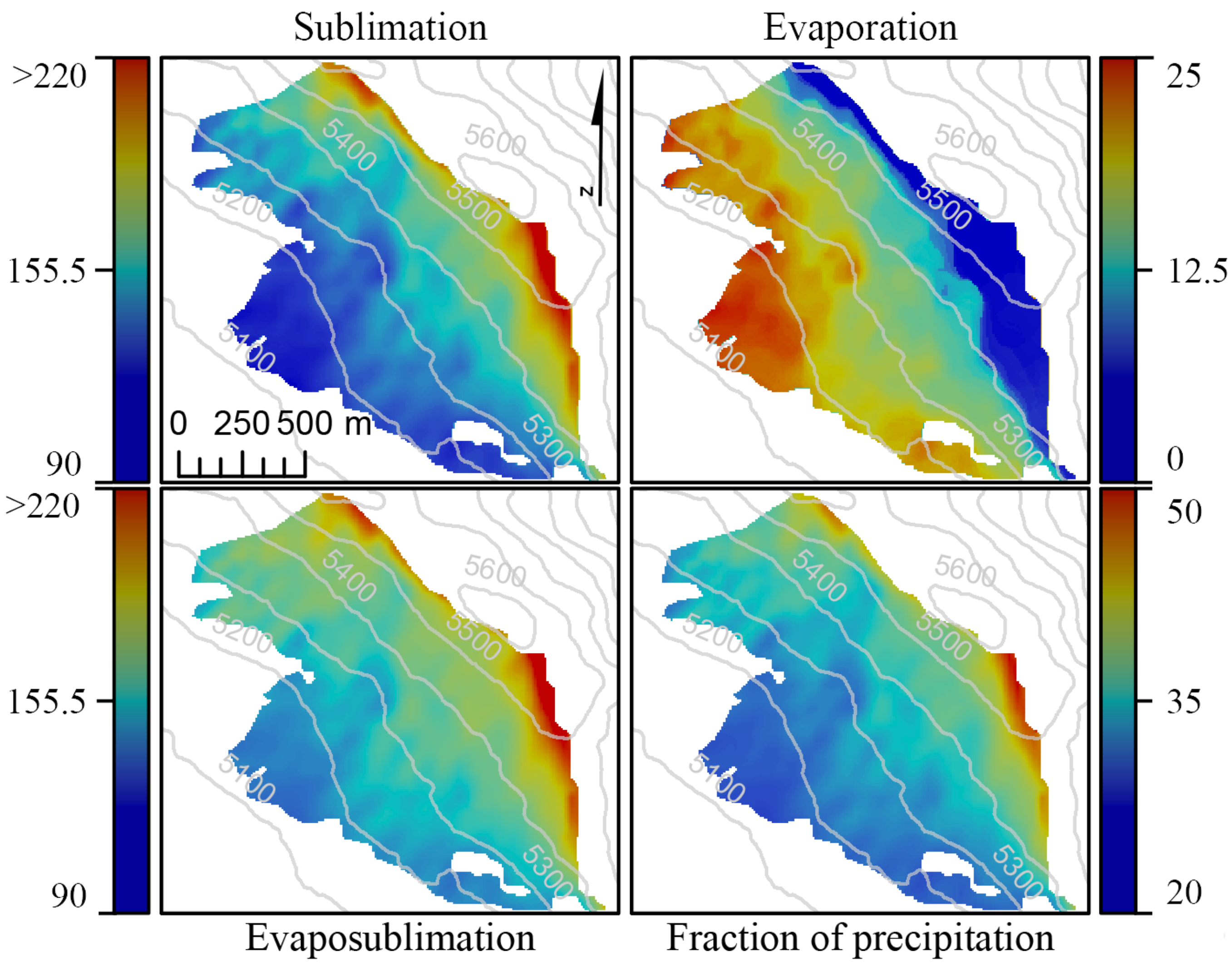


Stigter et al. 2018

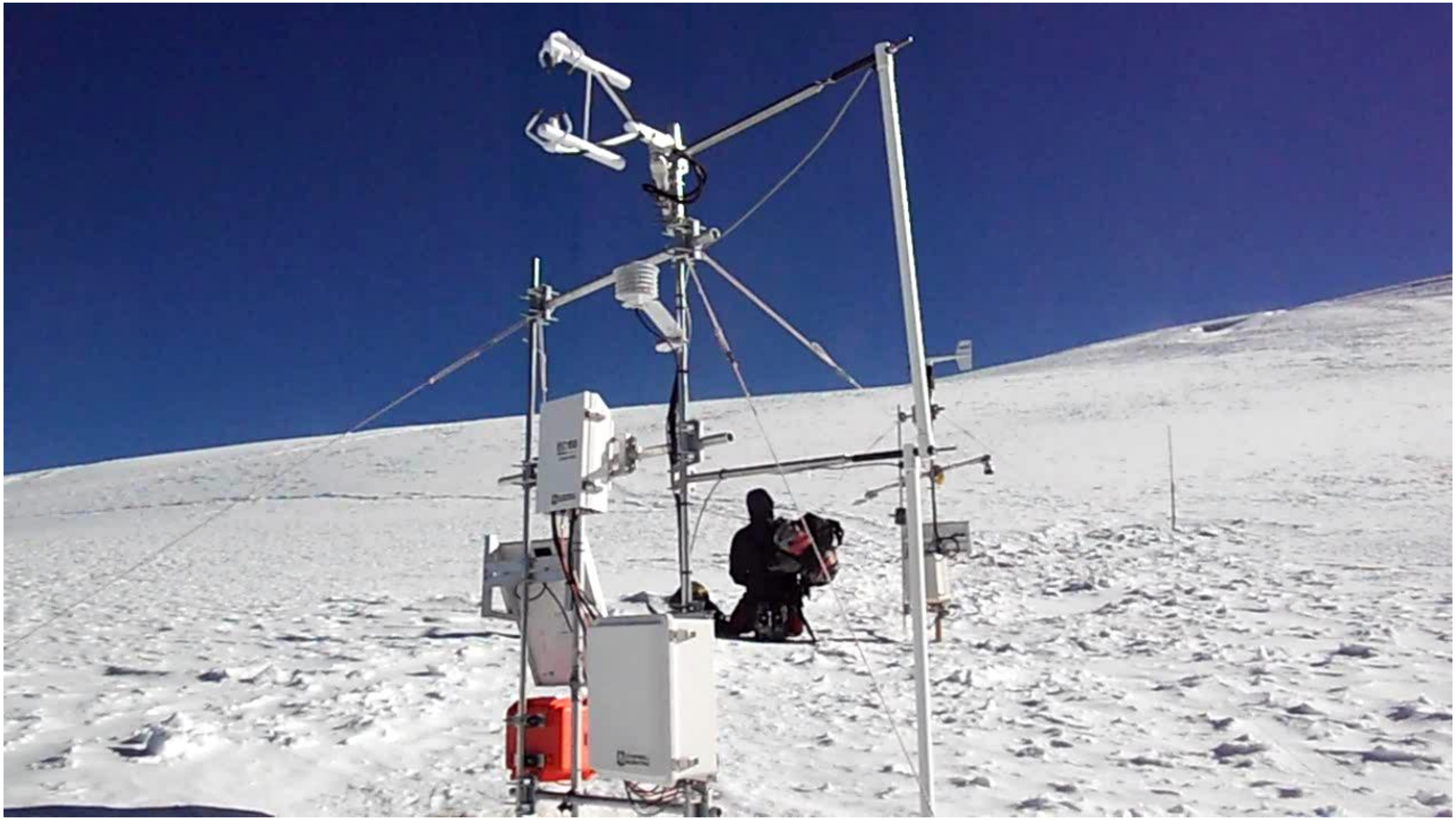
Sublimation

Sublimation

Sublimation



Sublimation



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Simplified snowmelt phases

- Three phases
  1. Warming phase
  2. Ripening phase
  3. Output phase

Warming phase

$$Q_{cc} = c_i \cdot \rho_w \cdot SWE \cdot (T_s - T_m)$$

Where:

Q_{cc} = cold content [MJ m^{-2}]

c_i = heat capacity of snow [MJ kg^{-1} K^{-1}]

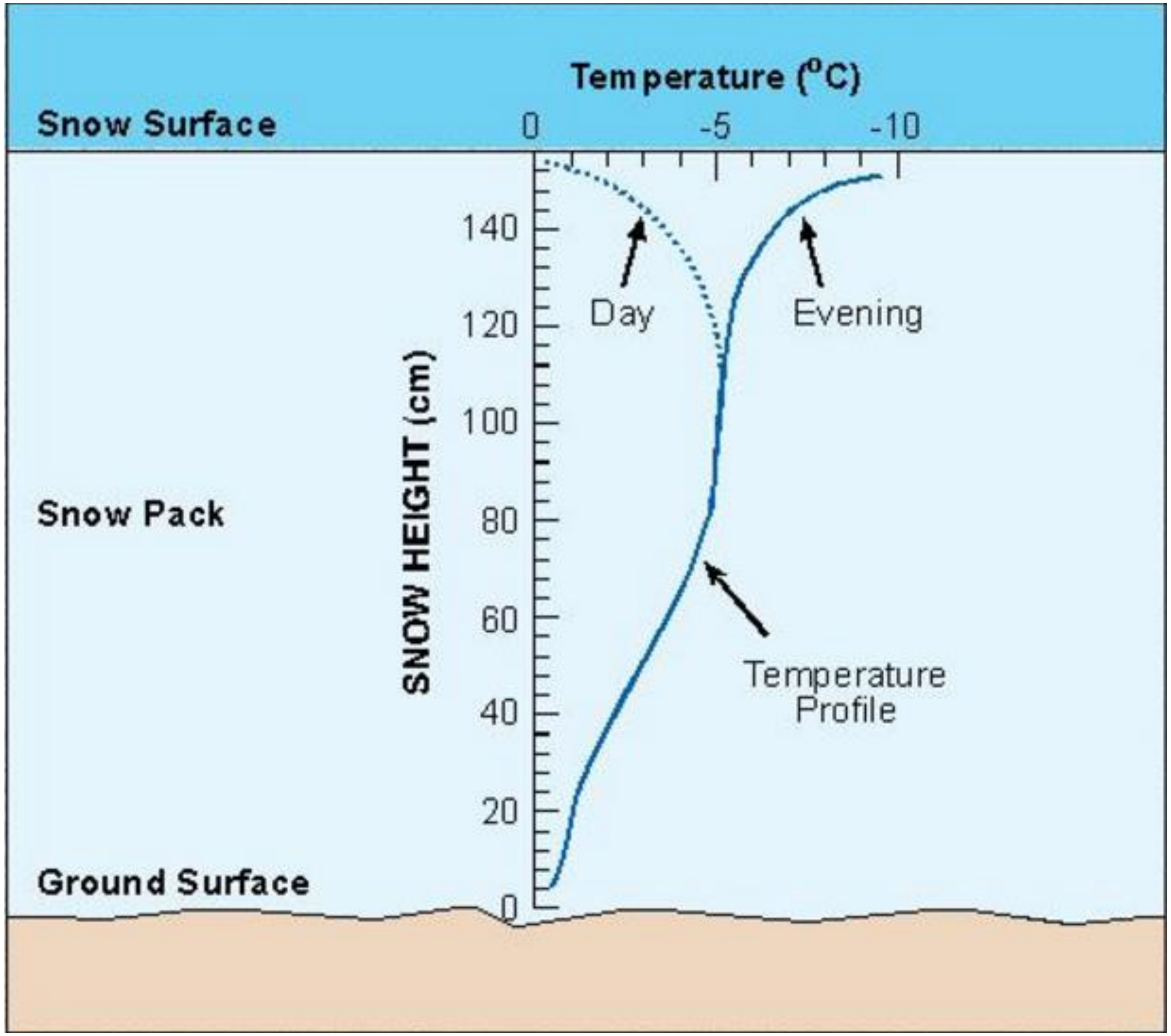
ρ_w = density of water [kg m^{-3}]

SWE = snow water equivalent [m]

T_s = snow temperature [K]

T_m = melting point of snow [K]

Warming phase



Ripening phase

$$\theta_{ret} = -0.0735 \cdot \left(\frac{\rho_s}{\rho_w}\right) + 2.67 \cdot 10^{-4} \cdot \left(\frac{\rho_s}{\rho_w}\right)^2$$

$$Q_{ripe} = \theta_{ret} \cdot h_s \cdot \rho_w \cdot \lambda_f$$

Where:

Q_{ripe} = energy required to complete ripening phase [MJ m^{-2}]

θ_{ret} = volumetric water content [-]

ρ_s = density of snow [kg m^{-3}]

ρ_w = density of water [kg m^{-3}]

λ_f = latent heat of fusion [0.334 MJ kg^{-1}]

h_s = snow depth [m]

Ripening phase

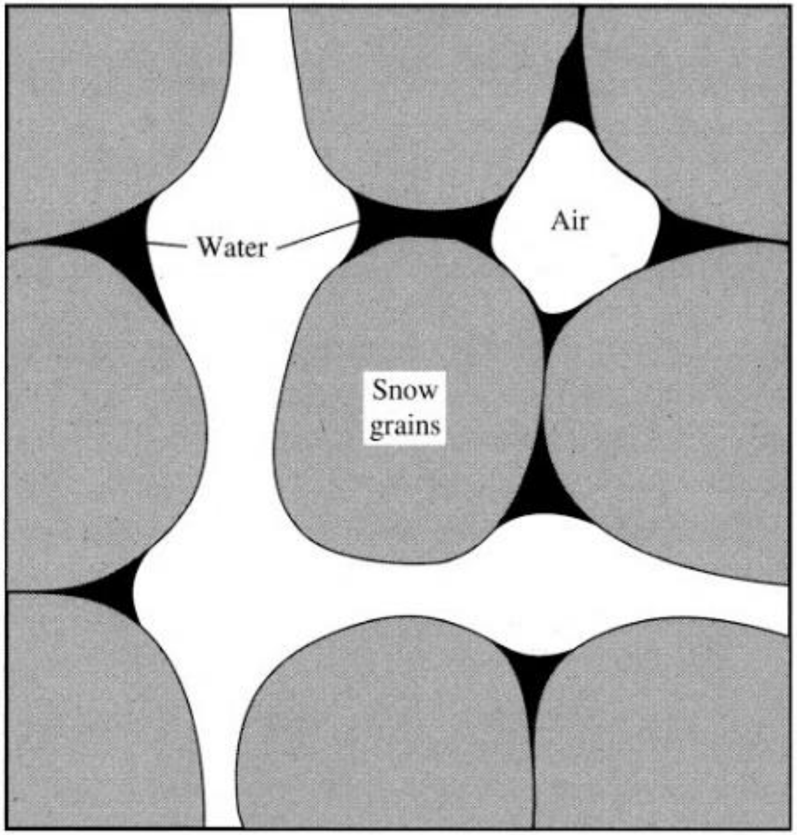


Figure 5.15 An idealized thin section of snow showing snow grains, water retained by surface tension, and continuous pores filled with air [adapted from Colbeck (1971)].

Output phase

$$Q_{out} = (h_m - h_{ret}) \cdot \lambda_f \cdot \rho_w$$

Where:

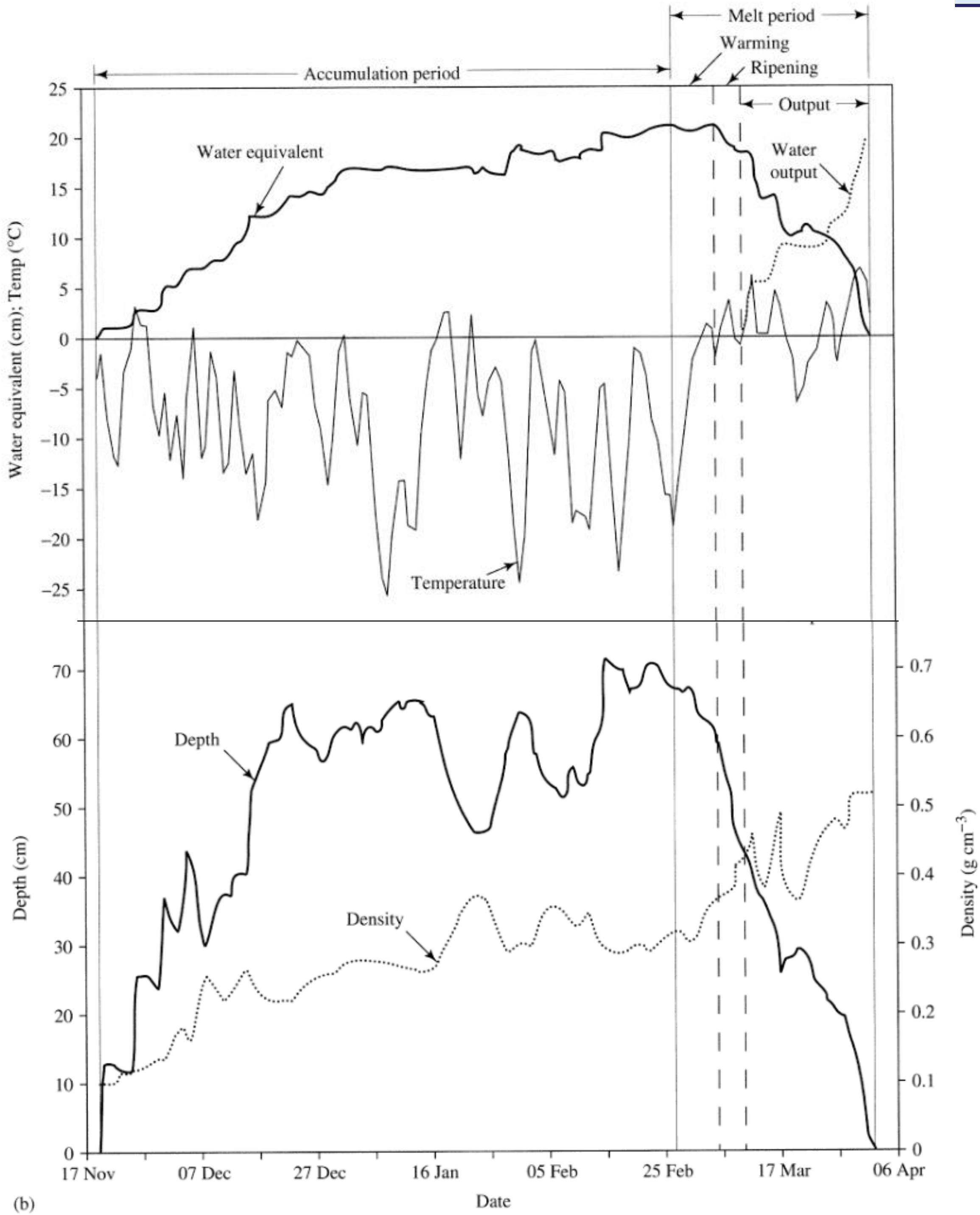
Q_{out} = energy required to complete output phase [MJ m^{-2}]

h_m = snow water equivalent [m]

h_{ret} = melt water retained in snowpack [m]

λ_f = latent heat of fusion [0.334 MJ kg^{-1}]

ρ_w = density of water [kg m^{-3}]



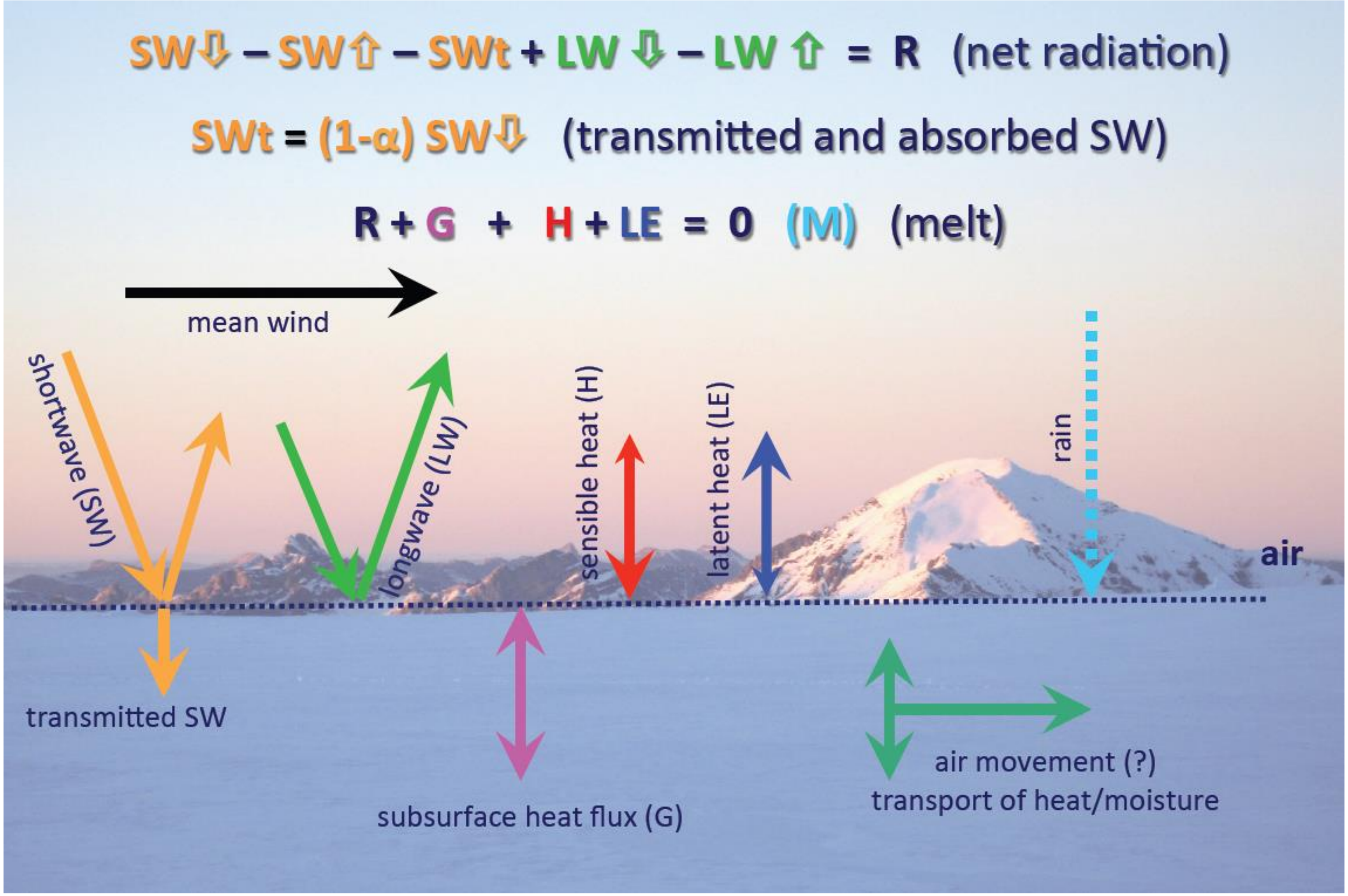
Melt period
Warming
Ripening
Accumulation period
Output
Water equivalent
Water output
Temperature
Water equivalent (cm); Temp (°C)
25
20
15
10
5
0
−5
−10
−15
−20
−25
Depth
Density
Depth (cm)
70
60
50
40
30
20
10
0
Density (g cm^{-3})
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
17 Nov
07 Dec
27 Dec
16 Jan
05 Feb
25 Feb
17 Mar
06 Apr
Date
(b)

Energy balance

$$\boxed{Q = Q_{cc} + Q_{ripe} + Q_{out}}$$

The sum of the energy absorption associated with the three snowmelt phases is the energy required to complete the snowmelt process

Energy balance of a snowpack



Prof. M Lehning

Energy balance of a snowpack

- $SW\downarrow$ = incoming shortwave radiation
- $SW\uparrow$ = outgoing shortwave radiation
- $LW\downarrow$ = incoming longwave radiation
- $LW\uparrow$ = outgoing longwave radiation
- H = sensible heat flux
- LE = latent heat flux
- G = Ground heat flux

Energy balance of a snowpack

- SW↓ = incoming shortwave radiation
- SW↑ = outgoing shortwave radiation

  SW↑ = (1 – α) SW↓

Energy balance of a snowpack

- LW↓ = incoming longwave radiation
- LW↑ = outgoing longwave radiation

  Stefan-Boltzman law:

  $$\boxed{LW = \sigma T^4}$$

  This assumes a 'black body'

  $$\boxed{LW\uparrow = \varepsilon \sigma T^4}$$

  However, snow is a gray body

Energy balance of a snowpack

Turbulent fluxes

- H = sensible heat flux

$$\boxed{H = \rho_a \, c_a \, C_h \, u \, (T_a - T_s)}$$

- LE = latent heat flux

$$\boxed{\mathrm{LE} = \lambda \, \rho_a \, C_e \, u \, (e_a - e_s)}$$

Energy balance of a snowpack

Where:

ρ_a = air density (kg m^{-3})

c_a = specific heat of dry air (J kg-1 K^{-1})

C_h = bulk transfer coefficient for sensible heat (-)

u = wind speed at elevation z (m s^{-1})

T_a = air temperature at elevation z (K)

T_s = snow temperature (K)

λ = latent heat of vaporization or sublimation (J kg^{-1})

C_e = bulk transfer coefficient for vapour exchange (-)

e_a = atmospheric vapor pressure at height z (Pa)

e_s = vapor pressure at the snowpack surface (Pa)

Water balance of a snowpack

$$\boxed{\frac{\Delta SWE}{\Delta t} = P - M\ (+) - S\ (+) - E}$$

$\Delta SWE / \Delta t$ = change in snow water equivalent through time

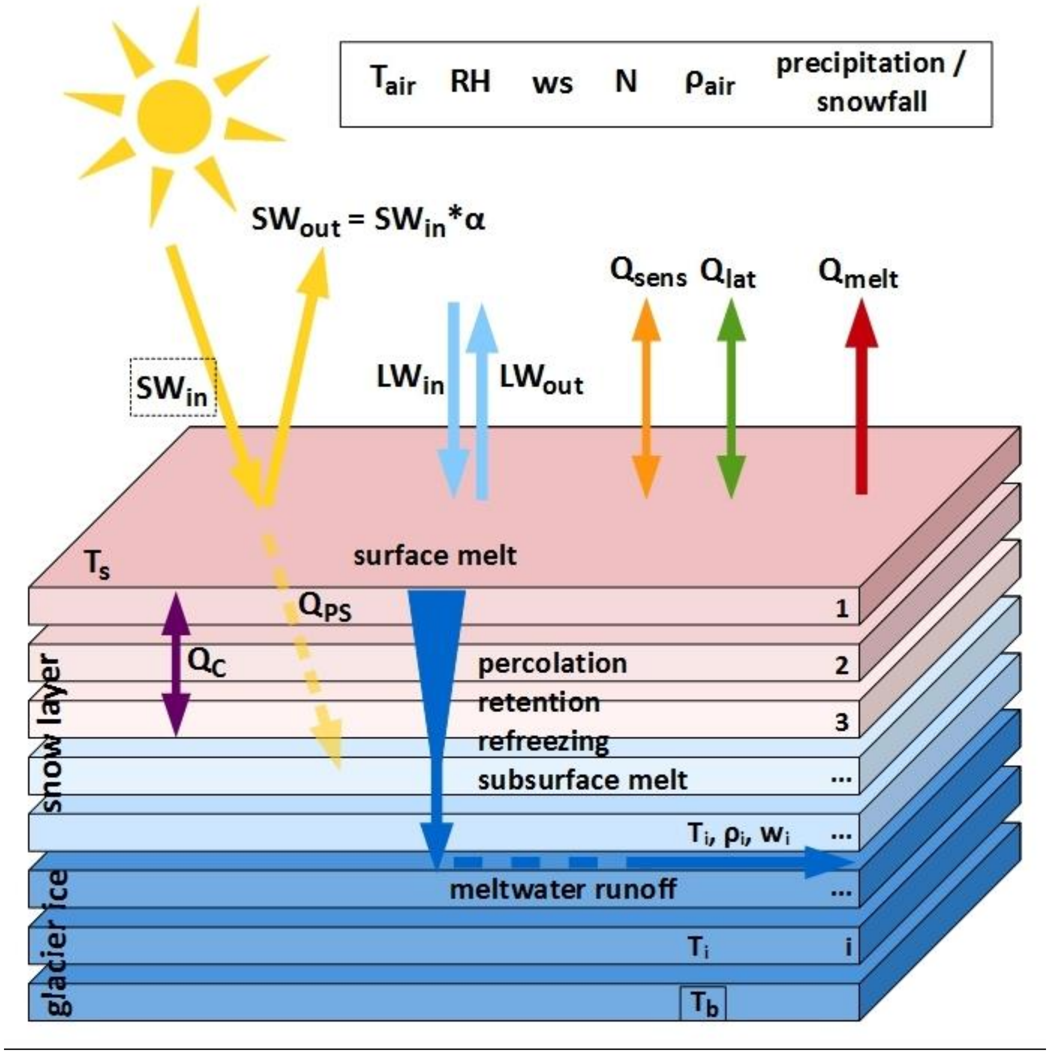
P = precipitation (snowfall)

M = melt

S = sublimation/deposition

E = erosion/deposition (wind transport and avalanching)

Mass balance coupled to energy balance



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Timing of snowmelt/runoff peak

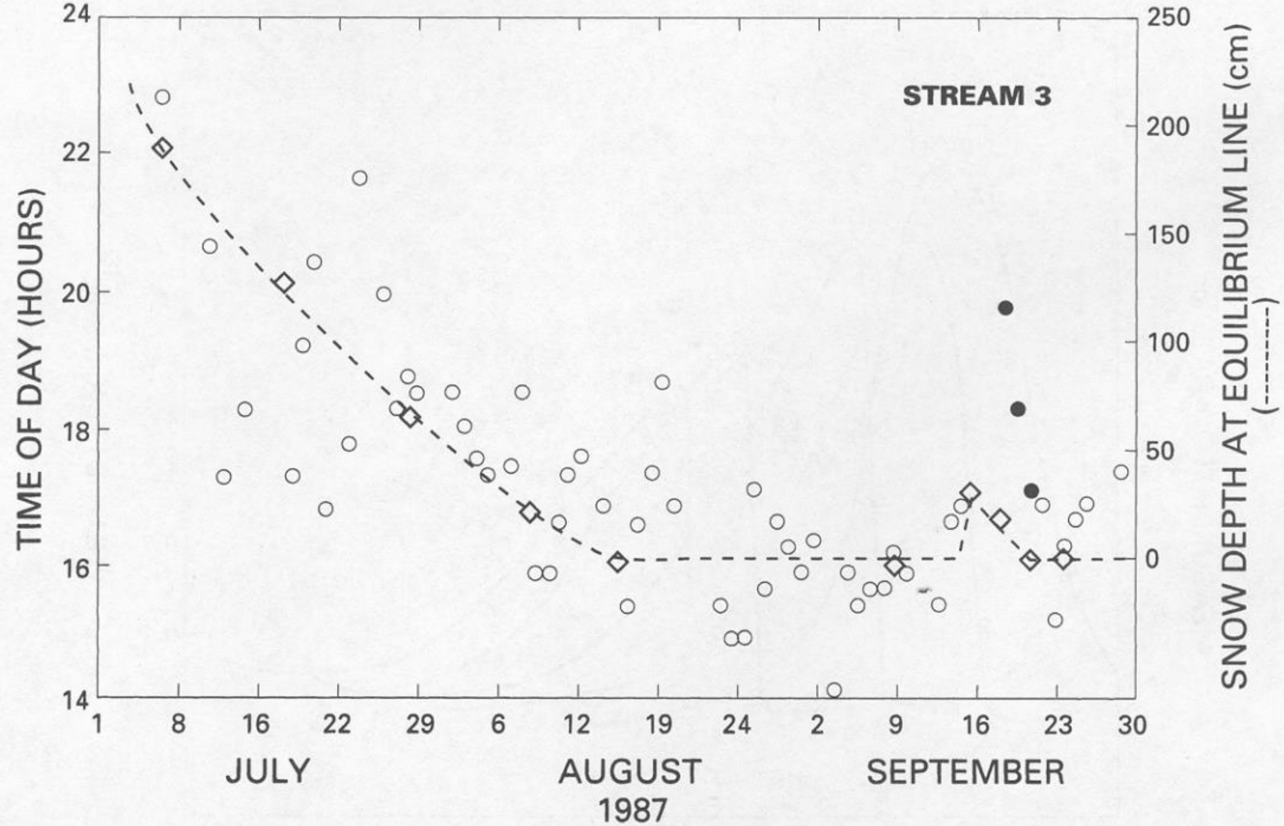


Figure 3. Time of daily peak water discharge for stream 3 at South Cascade Glacier, Washington, USA. The broken line is the interpolated snow depth at the equilibrium line; open diamonds indicate measured thickness; closed circles are times of peak daily discharge following a snowfall (adapted from Fountain, 1992b). Reproduced courtesy of the International Glaciological Society from the *Journal of Glaciology*, 1992, **38** (128), 191, figure 2

Water movement through snow

- Liquid water contents ~6% in pore space
- Surface and capillary tension
- Drainage of meltwater as result of gravity

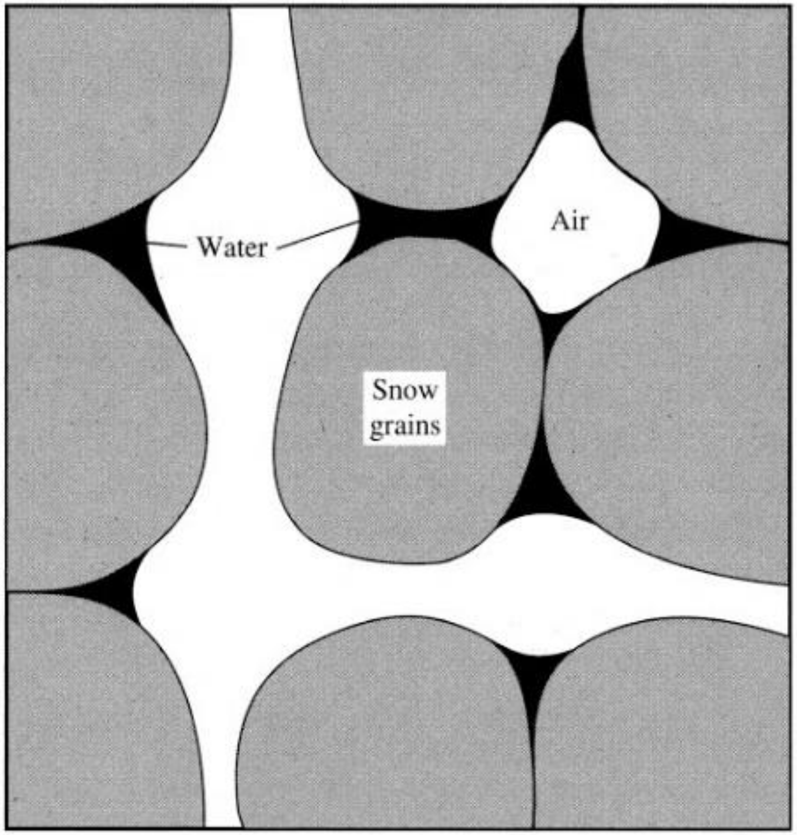


Figure 5.15 An idealized thin section of snow showing snow grains, water retained by surface tension, and continuous pores filled with air [adapted from Colbeck (1971)].

Water movement through snow

- Flow through a porous media - Darcy's law

$$u = \frac{k_w}{\mu} \cdot \left(\frac{\partial p_c}{\partial z} + \rho_w g \right)$$

Water movement through snow

- Flow through a porous media - Darcy's law

$$u = \frac{k_w}{\mu} \cdot \left(\underbrace{\boxed{\frac{\partial p_c}{\partial z}}}_{\text{Pressure gradient}} + \underbrace{\boxed{\rho_w g}}_{\text{Gravity}} \right)$$

Snow hydrology

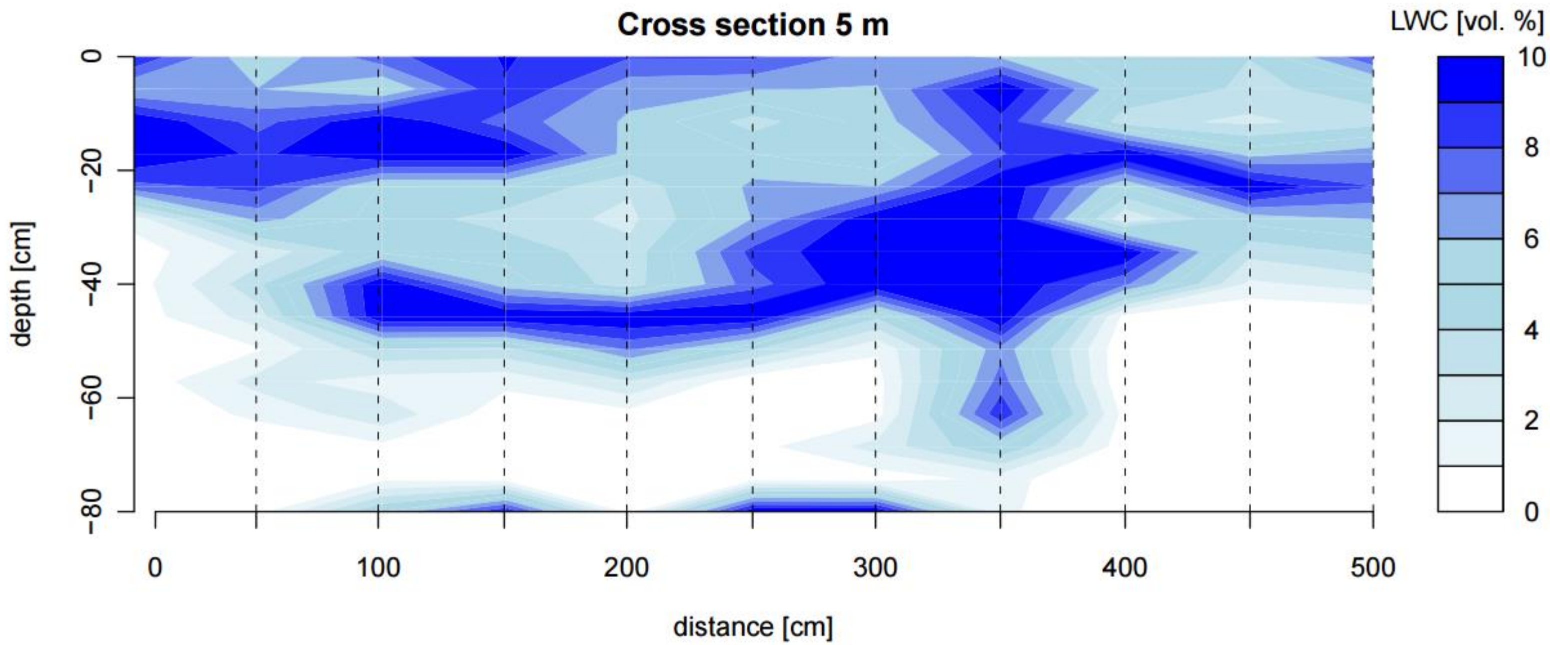
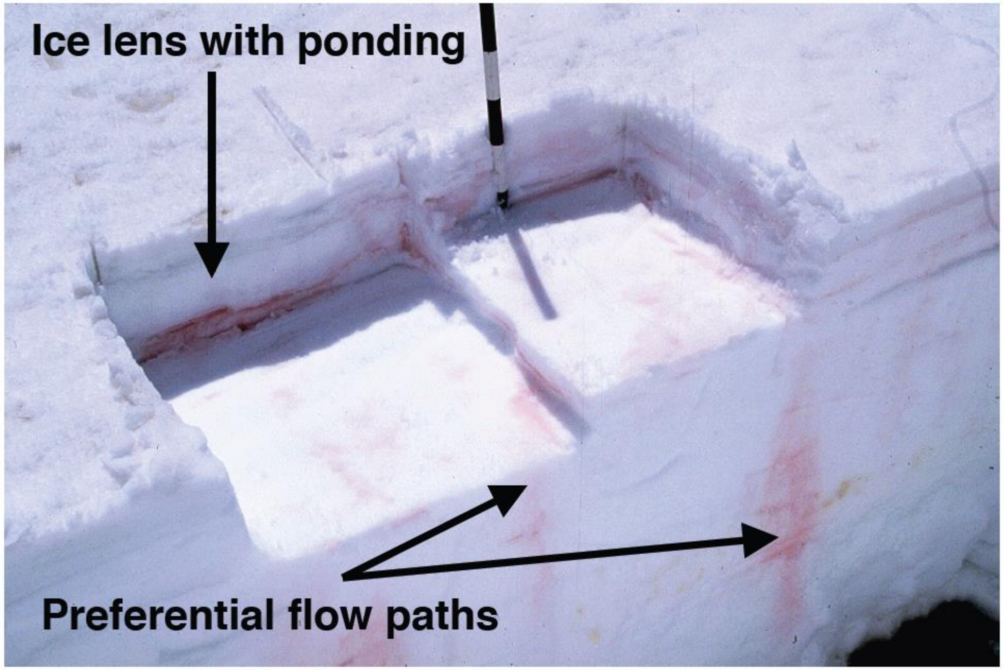


Fig. 5. Contour plot showing cross-section of snow wetness (θ) to a depth of 80 cm over 5 m wide areas across the slope. Measurements were conducted at horizontal intervals of 50 cm (lines) with a vertical spacing of 5 cm. 4 April 2009, S aspect, 2660 m, 30°. θ, measured with the Snow Fork, is corrected by −0.8 vol. % (this corresponds to the median offset in dry snow).

Techel and Pielmeier, 2011 (TC)

Snow hydrology

- Preferential flow
- Ice layers (impermeable)



Prof. M. Lehning

M. Rheim

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Measuring snow

Snowfall

- pluviometer
- heated tipping bucket

Measuring snow

Snow depth

- sonic range sensor
- laser sensor
- probes

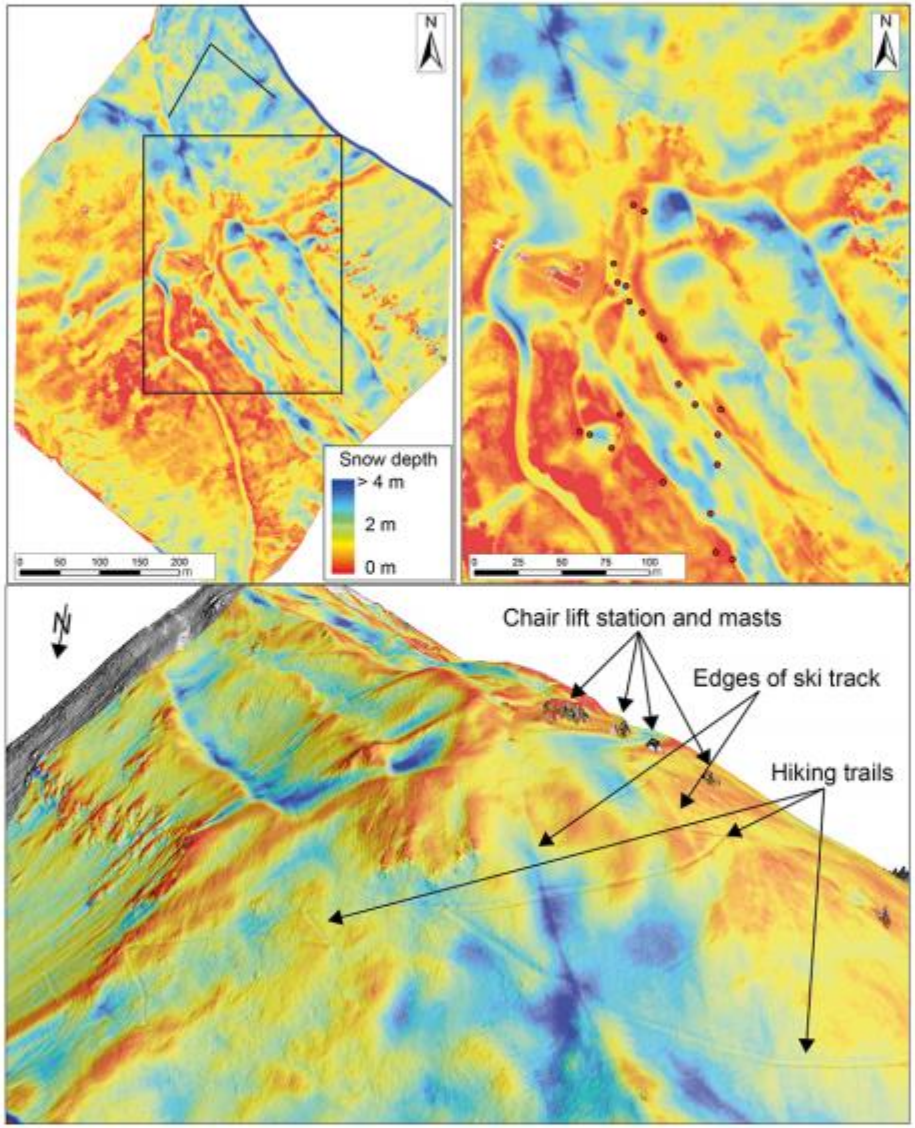


Figure 6. Overall HS map of the Brämabühl test site (top left panel) and close-up of the central part (top right panel). The locations of the reference plots are displayed as red circles. 3-D view of the HS draped over the hillshade of the snow-free DSM facing from north to south (bottom panel).

Buehler et al, 2016 (TC)

Measuring snow

Snow water equivalent

- snow pits
- snow pillows
- gamma-ray sensor

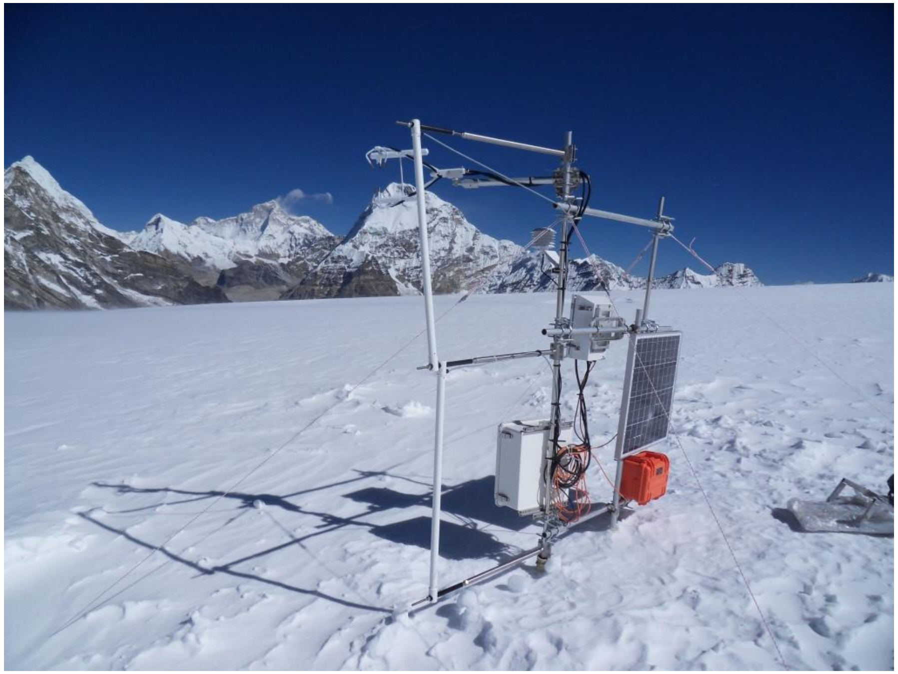
Measuring snow

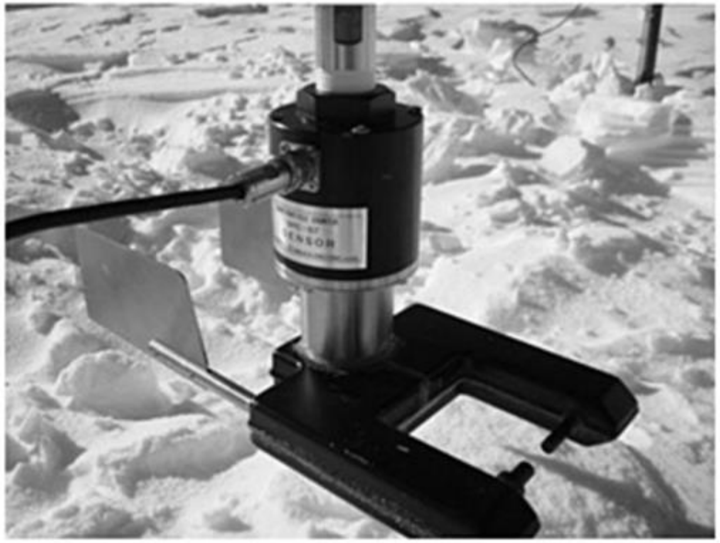
Snow water equivalent

Measuring snow

Snow transport

- acoustic sensors
- particle counters
- catch





Nishimura et al. (2014)

Cierco et al. (2007)

Measuring snow

Snowmelt runoff

- lysimeter

- river discharge

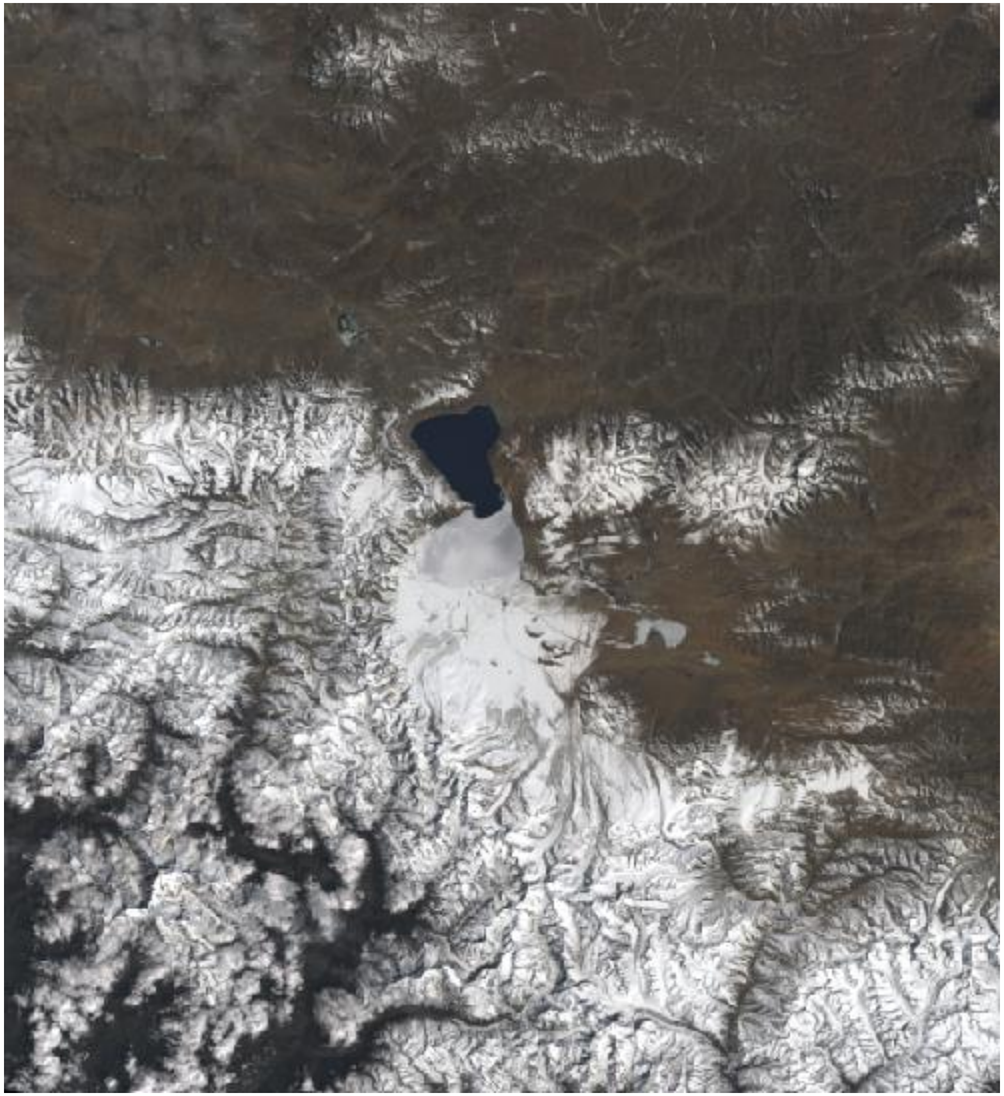
Measuring snow

Snowmelt runoff

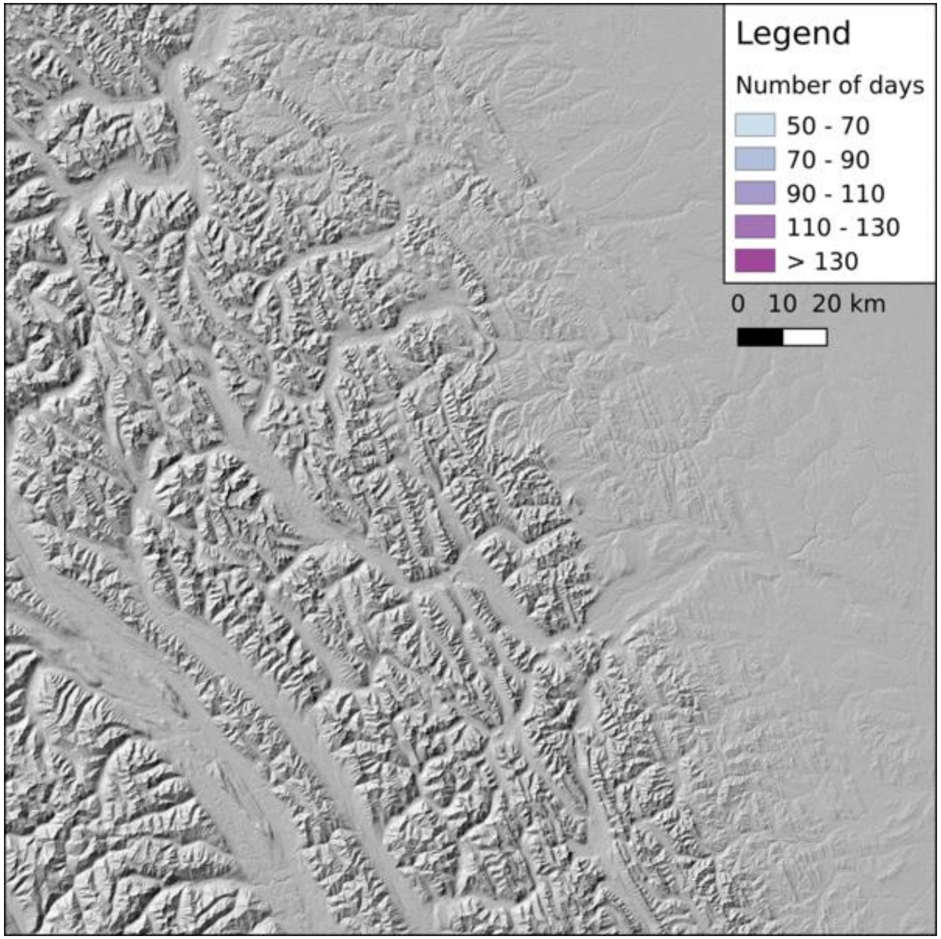
- lysimeter
- river discharge

Measuring snow

- Snow extent
  - Remote sensing

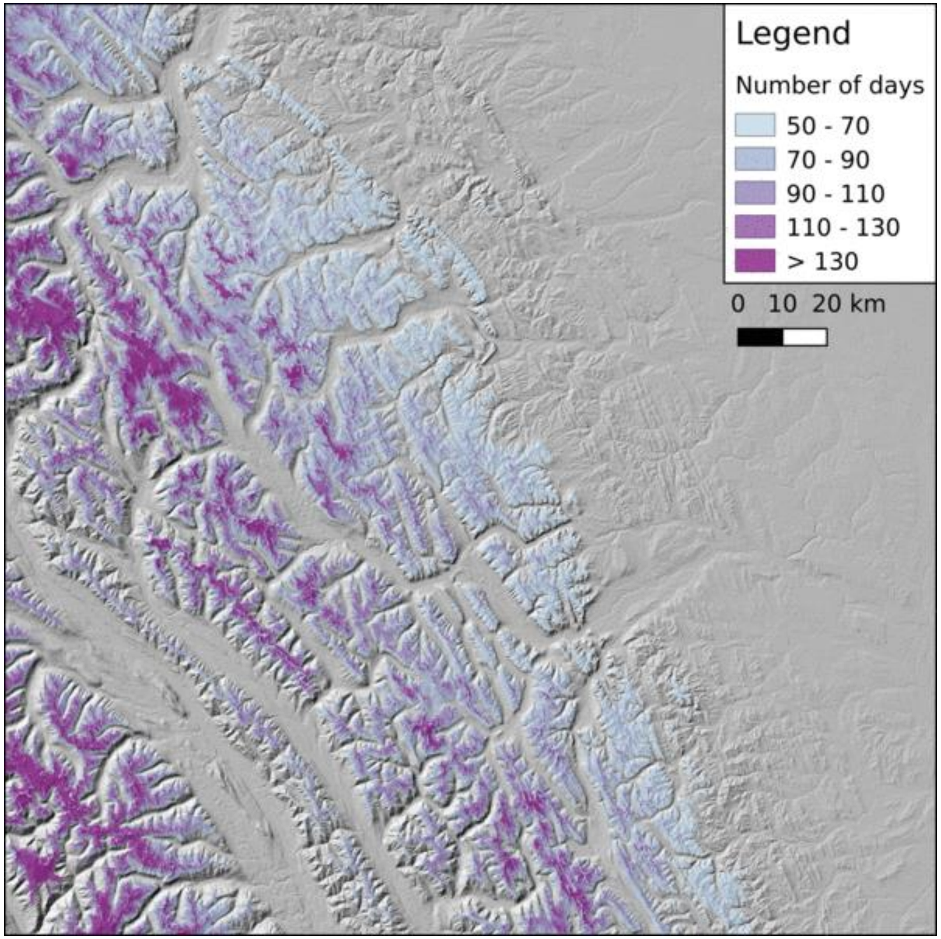


Measuring snow – from space



Gascoin Simon, Sentinel 2

Measuring snow – from space



Gascoin Simon, Sentinel 2

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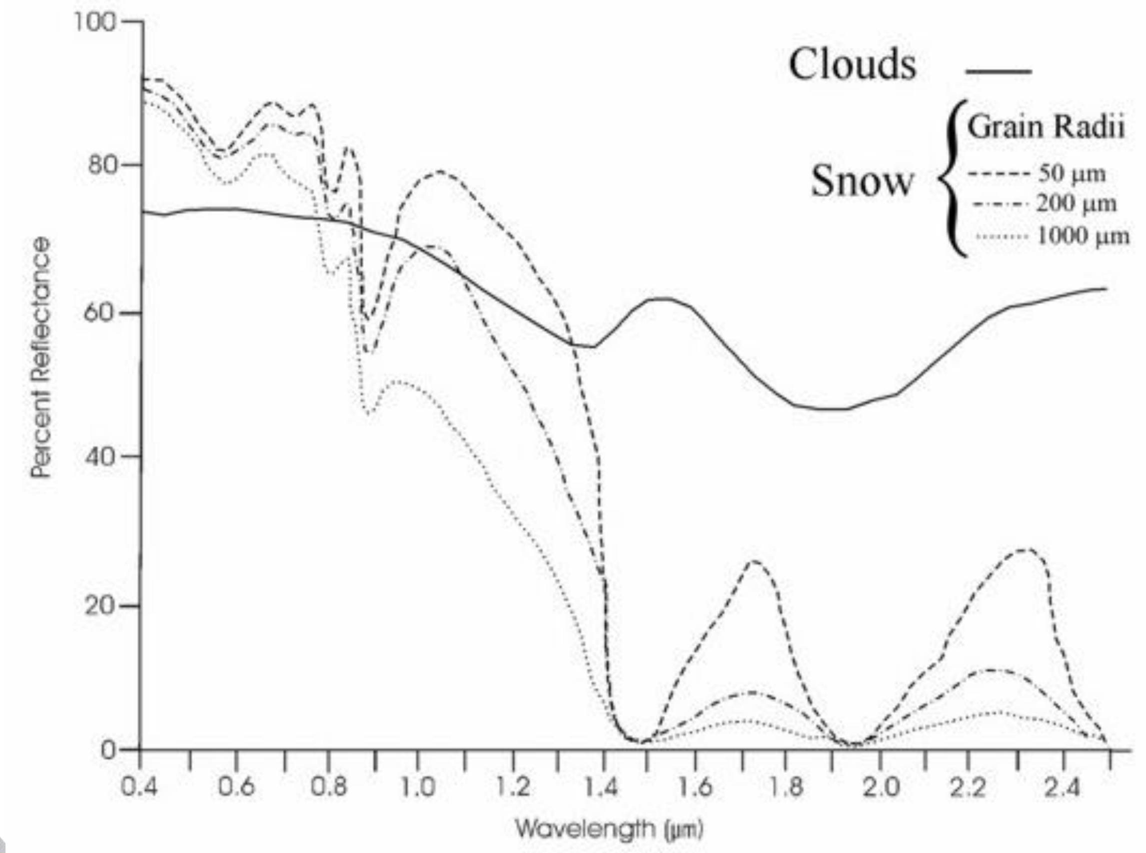
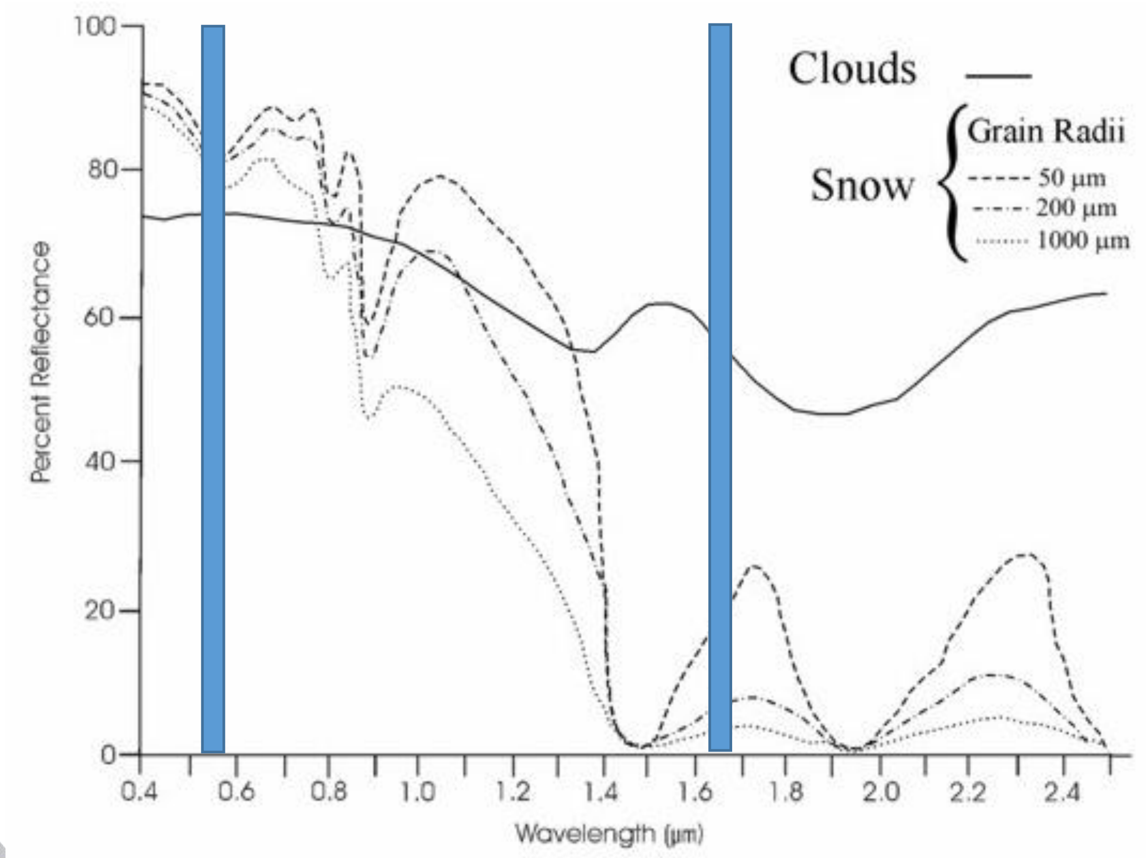
Remote sensing of snow

Reflectance in different parts of the electromagnetic spectrum



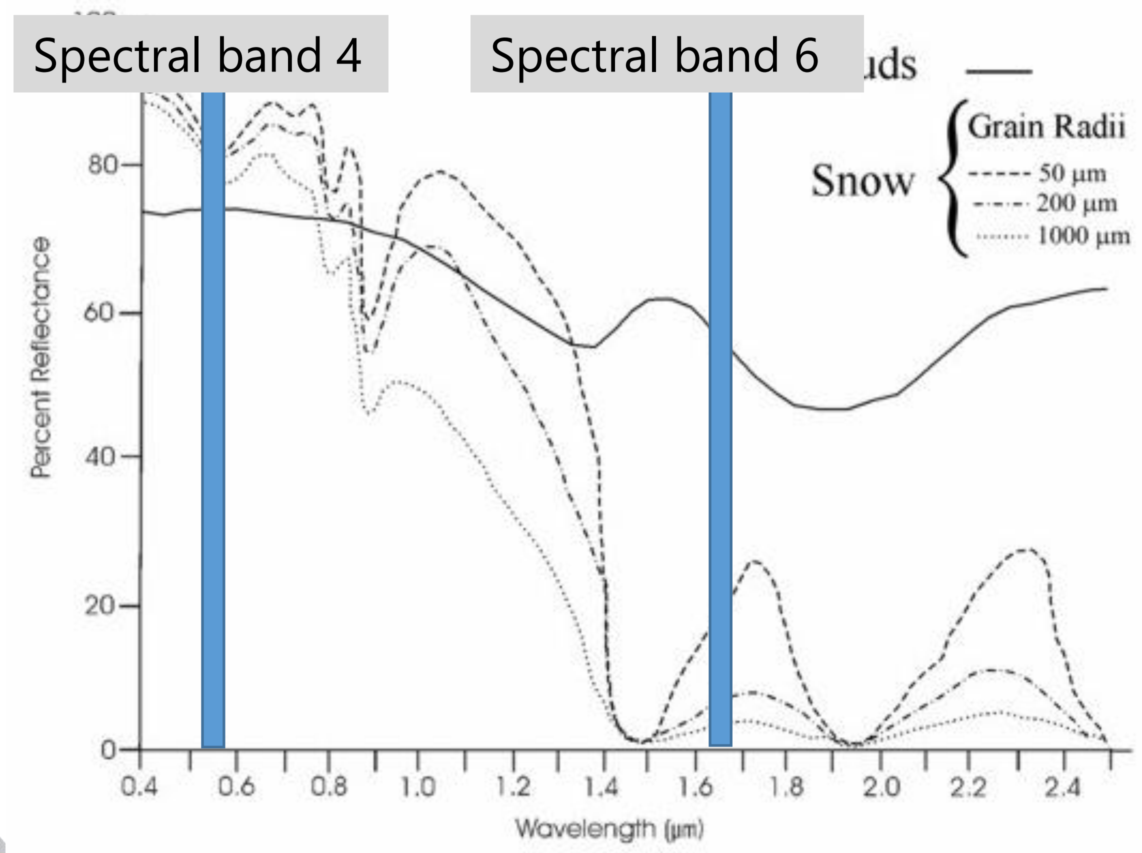
Remote sensing of snow

MODIS – Moderate Resolution Imaging Spectroradiometer



Remote sensing of snow

MODIS – Moderate Resolution Imaging Spectroradiometer



Remote sensing of snow

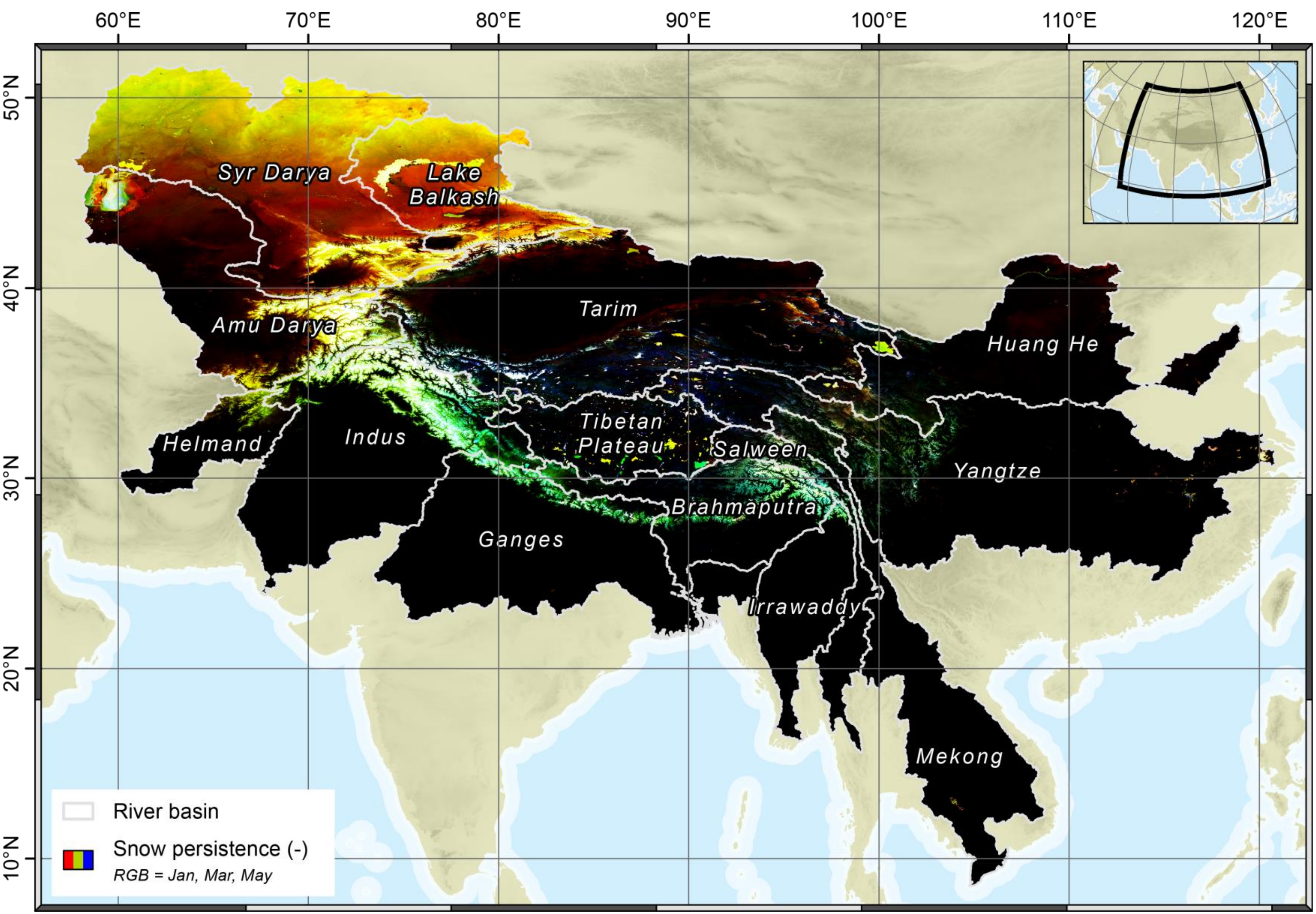
Normalized Difference Snow Index (NDSI):

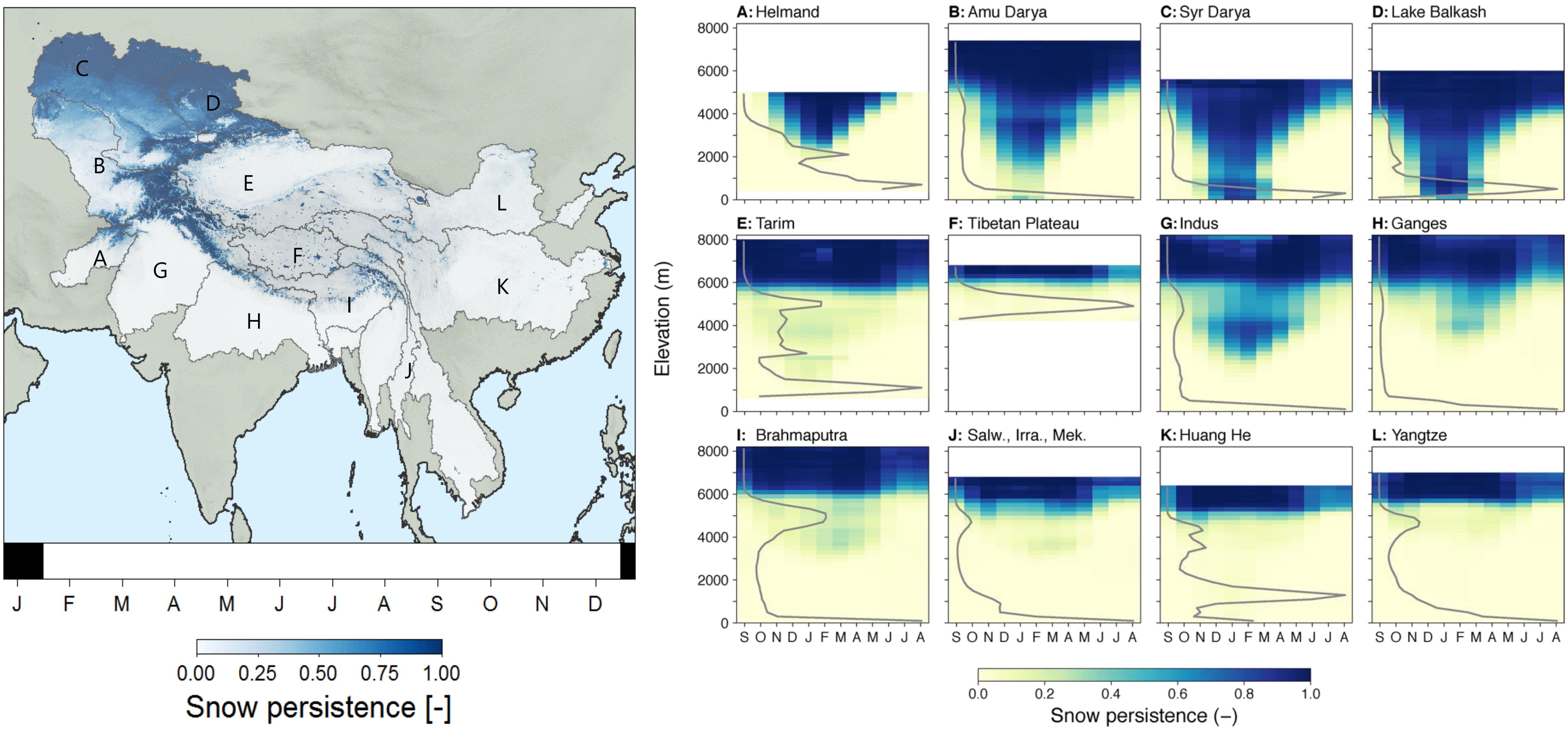
$$NDSI = \frac{Green - SWIR}{Green + SWIR}$$

if $NDSI \geq 0.4 \rightarrow \text{snow}$

For MODIS sensor:

$$NDSI = \frac{Band\ 4 - Band\ 6}{Band\ 4 + Band\ 6}$$


60°E
70°E
80°E
90°E
100°E
110°E
120°E
50°N
40°N
30°N
20°N
10°N
Syr Darya
Lake Balkash
Amu Darya
Tarim
Huang He
Tibetan Plateau
Helmand
Indus
Salween
Yangtze
Brahmaputra
Ganges
Irrawaddy
Mekong
River basin
Snow persistence (-)
RGB = Jan, Mar, May



C
D
B
E
L
A
G
F
K
I
H
J
J F M A M J J A S O N D
0.00 0.25 0.50 0.75 1.00
Snow persistence [-]
A: Helmand
B: Amu Darya
C: Syr Darya
D: Lake Balkash
E: Tarim
F: Tibetan Plateau
G: Indus
H: Ganges
I: Brahmaputra
J: Salw., Irra., Mek.
K: Huang He
L: Yangtze
Elevation (m)
8000
6000
4000
2000
0
S O N D J F M A M J J A
0.0 0.2 0.4 0.6 0.8 1.0
Snow persistence (–)

Snowmelt Runoff Model (SRM)

$$\boxed{\mathrm{Q}_{\mathrm{n+1}} = kQ_n + (1-k)(a\,T\,A + P)}$$

Q_{n+1} = discharge ($m^3 s^{-1}$)

k = recession coefficient (-)

a = degree day factor ($cm\ ℃^{-1}\ d^{-1}$)

T = air temperature (℃)

A = snow covered area (km^2)

P = precipitation (cm)

Simulating snow(melt)

Two approaches:

- Energy-balance approach
  Based on full energy balance

- Temperature-index approach
  Melt is a function of air temperature

Simulating snow(melt)

Two approaches:

- Energy-balance approach

$$\boxed{R+G+H+LE = 0}$$

- Temperature-index approach

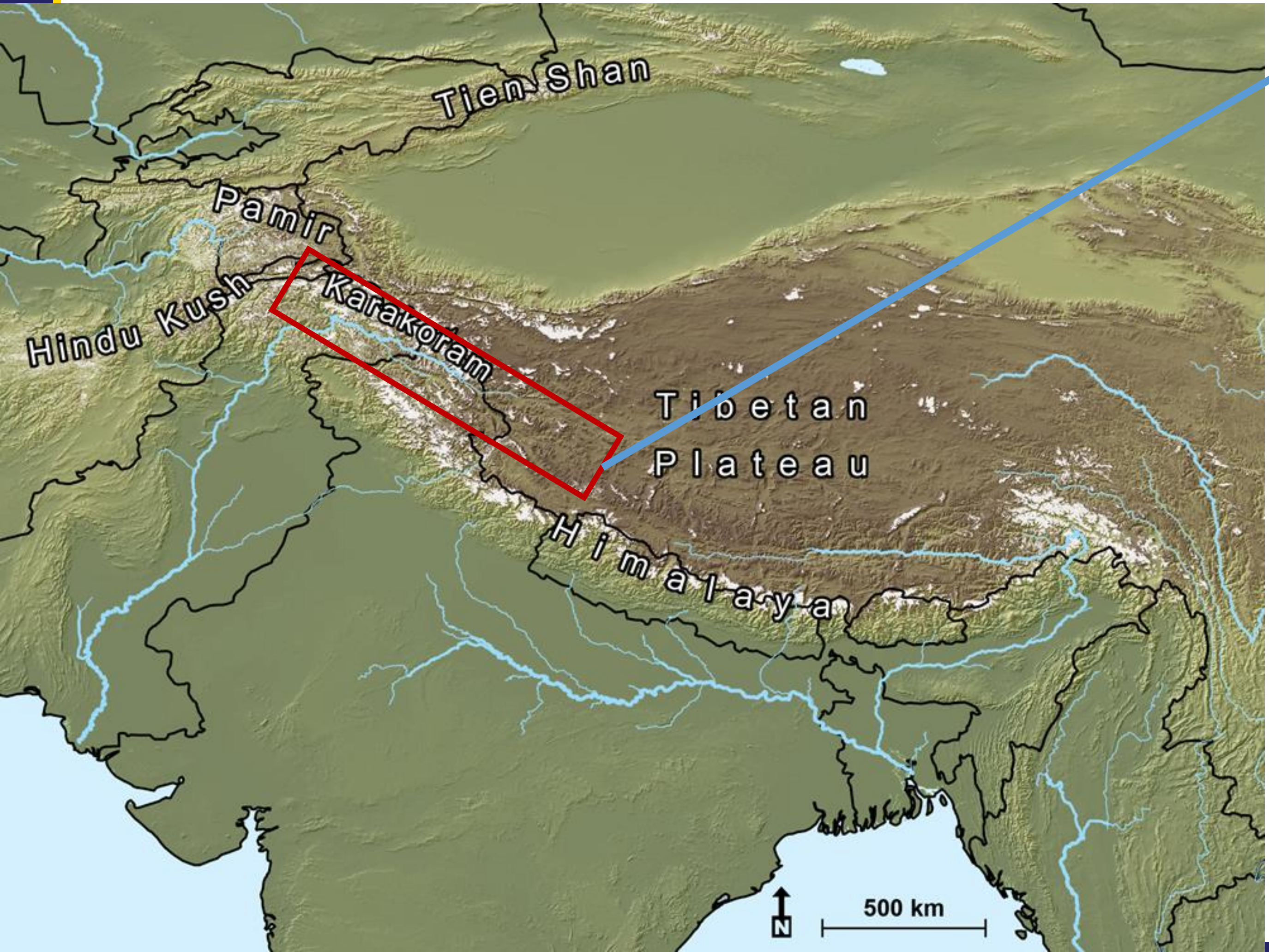
$$\boxed{M(t) = b \cdot PDD(t)}$$

$M(t)$ = melt (mm)

b = empirical factor (mm °C^{-1})

$PDD(t)$ = positive degree day (°C)

Case study - Study area



upper Indus basin

Case study

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Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing

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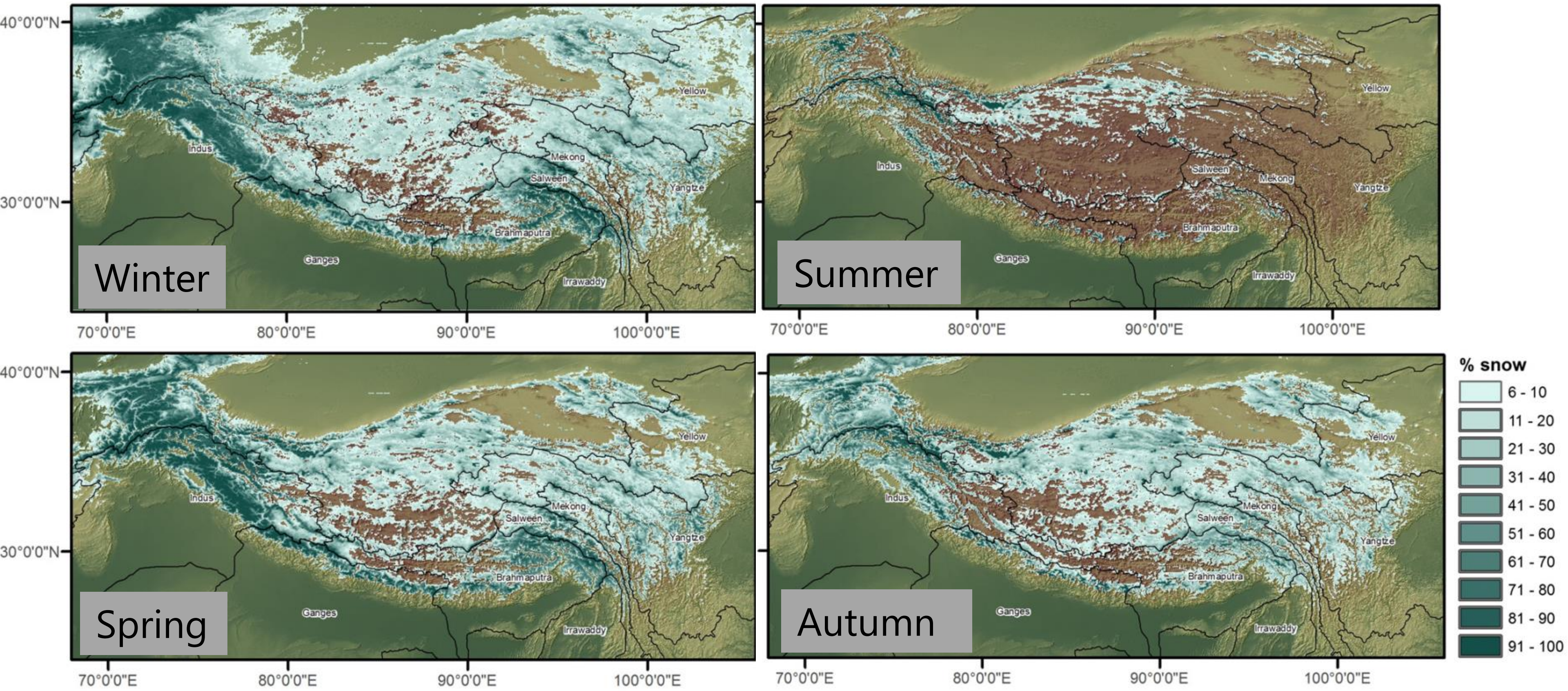
[b] Utrecht University, Department of Physical Geography, PO Box 80115, Utrecht, The Netherlands

- Analysis of spatial- temporal snow cover dynamics
- Estimate runoff and effect of climate change

Results



Winter
Summer
Spring
Autumn
40°0'0"N
30°0'0"N
70°0'0"E
80°0'0"E
90°0'0"E
100°0'0"E
Indus
Ganges
Brahmaputra
Salween
Mekong
Yangtze
Yellow
Irrawaddy
% snow
6 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100

Results

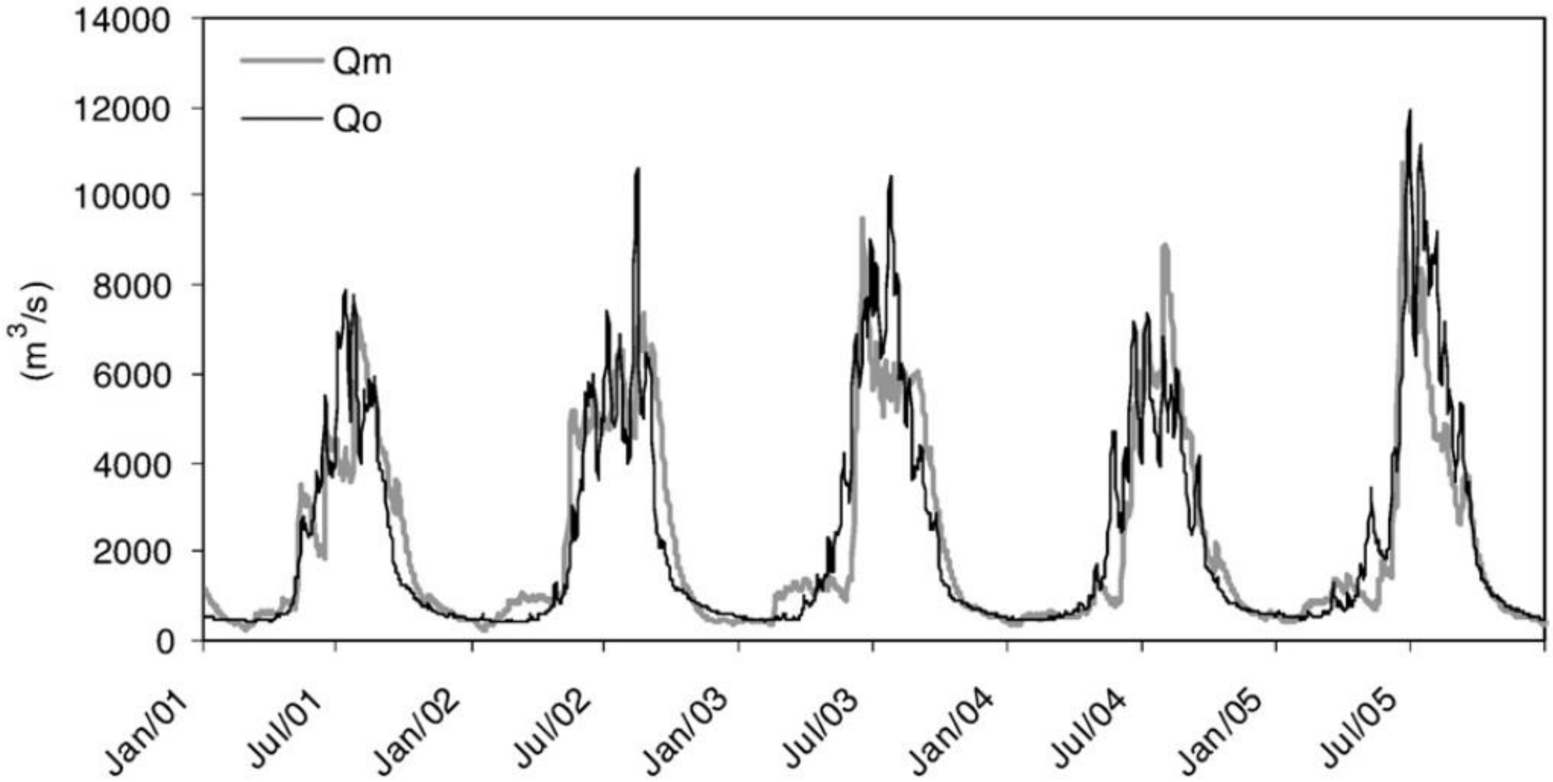
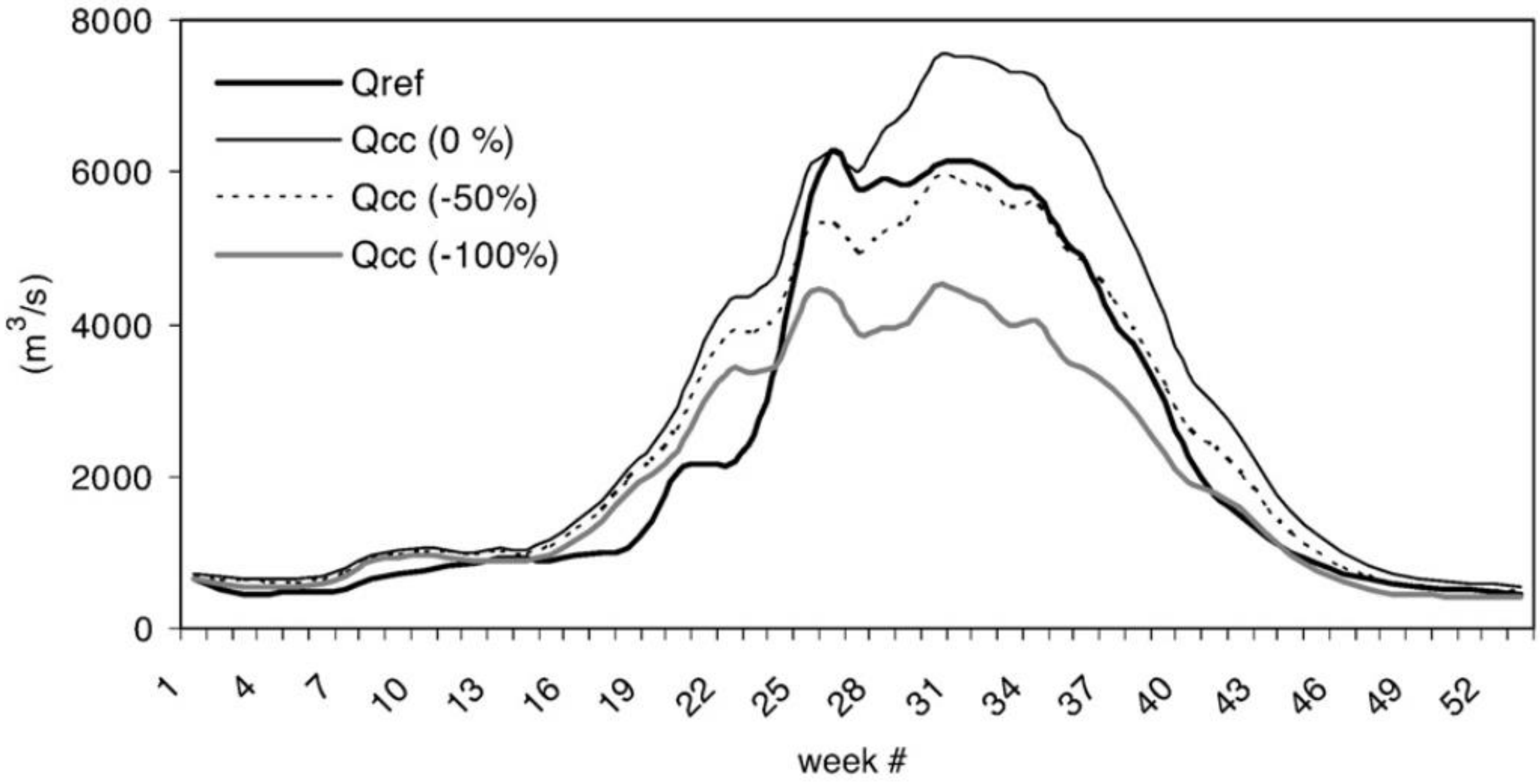


Fig. 7. Modelled and observed daily stream flow at Besham Qila from 2001 to 2005.

Results



8000
6000
4000
2000
0
(m^3/s)
Qref
Qcc (0 %)
Qcc (-50%)
Qcc (-100%)
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
52
week #


Thank you for your attention!