# Regional pattern of annual snow cover duration in the Greater Alpine Region

Markus Hrachowitz

# The value of real team work

## A big "Thank You" to all involved so far

Stefan Fugger

Chris Bouman

Karsten Schulz

Susan Steele-Dunne

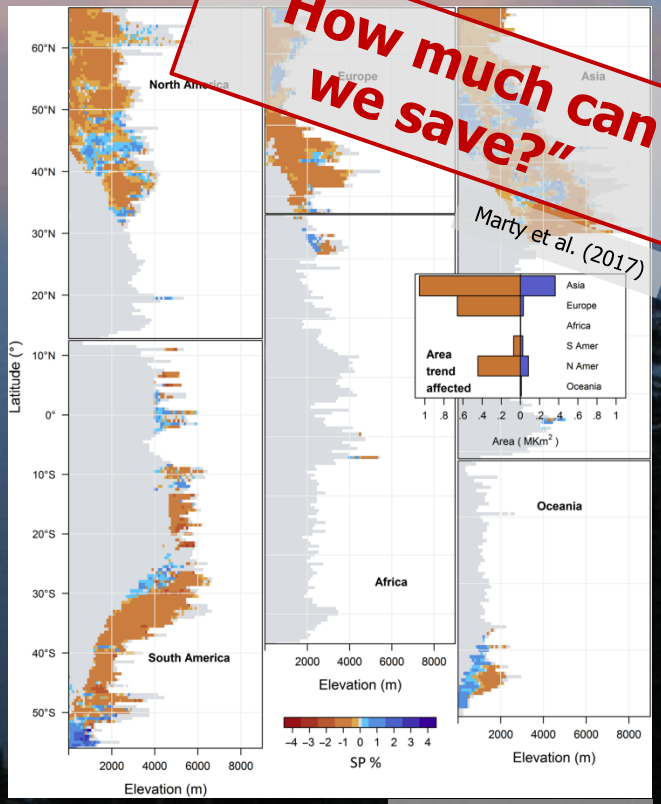
...and many others:
Katalin Bene, Marco Borga, Thijs van Esch, Matthew Herrnegger, Qiaodan Liu, Duro Parajka, Francesca Pellicciotti, Daniele Penna

# Seasonal snow pack

## Life-line of societies and ecosystems in the Northern Hemisphere

Seasonal snow pack
- affects timing and magnitude of spring floods
- sustains summer low flows

Relevance for
- Drinking water
- Hydropower production
- Agricultural water supply
- Industrial water supply
- Shipping
- Recreational industry

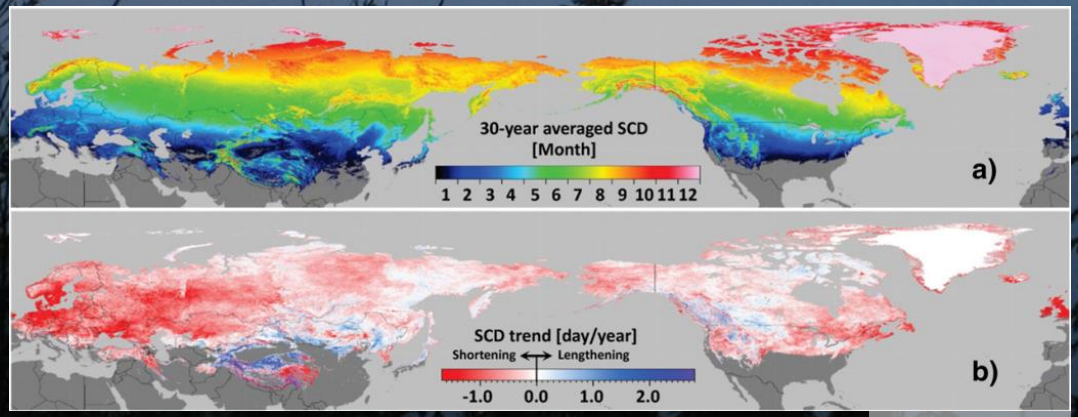


# Annual snow cover duration ($D_{SC}$)

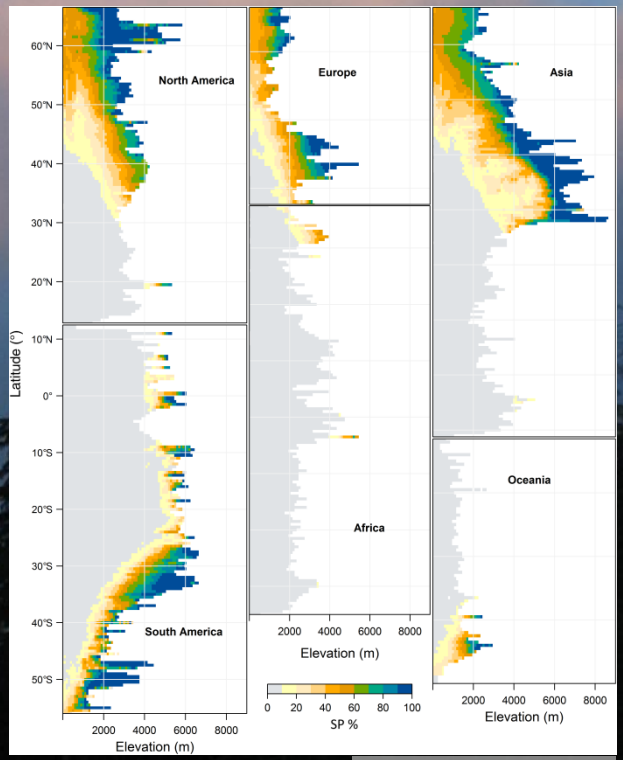
## What do we know?

What is it?
Number of days in a year a given location is covered by snow.

Why is it useful?
Less information content than SWE, but directly observable at larger scales and thus lower uncertainties




Hori et al. (2017)




Hammond et al. (2018)

# Annual snow cover duration ($D_{SC}$)

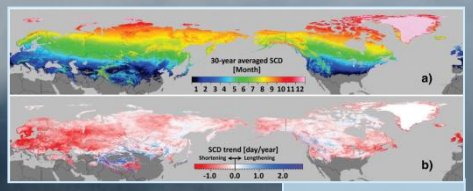
## What is the knowledge gap?

**Observation-based studies**

**Modelling studies**

### Remote-sensing data

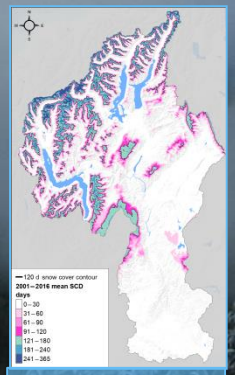
**Global scale**




Hori et al. (2017)

- Low temporal resolution (e.g. NOAA AVHRR)
- Little detail

**Local scale**

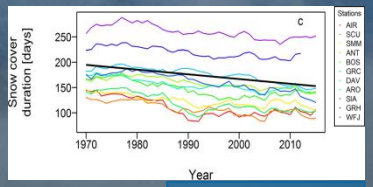



Redpath et al. (2019)

- Little regional context
- Not generalizable

### In-situ observations

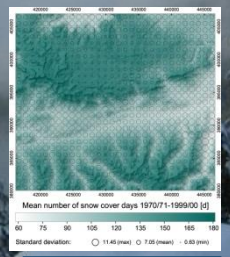
**Point-scale**




Klein et al. (2016)

- Very scarce
- No spatial context
- Not generalizable

**Local to global scale**



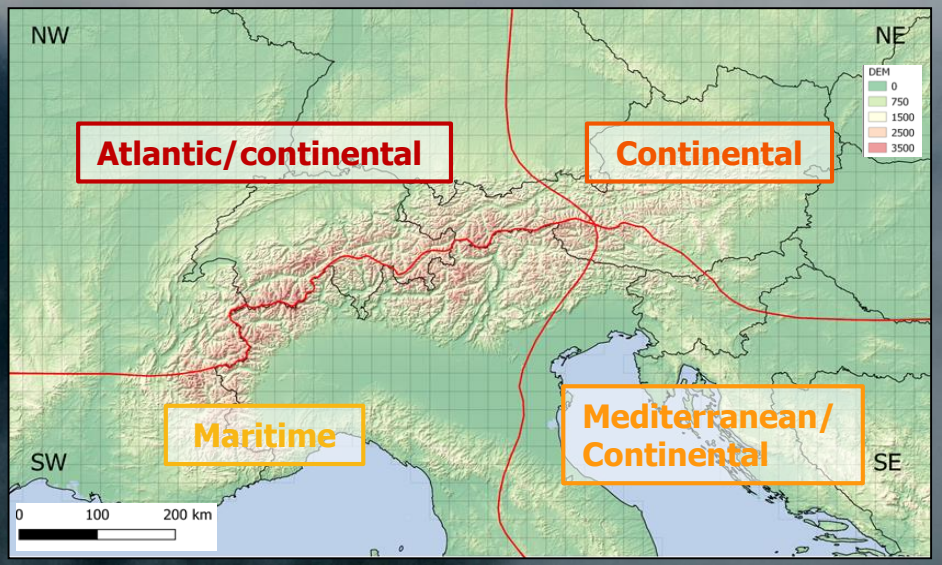

Marke et al. (2015)

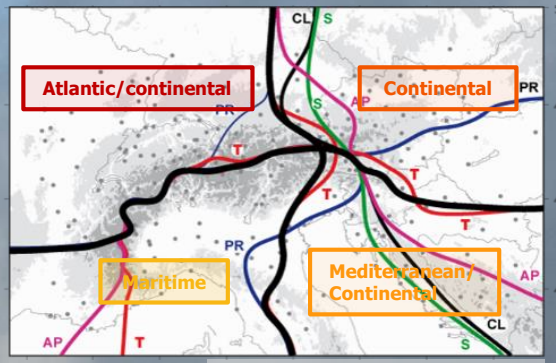
- Data uncertainty
- Model uncertainty

# Annual snow cover duration

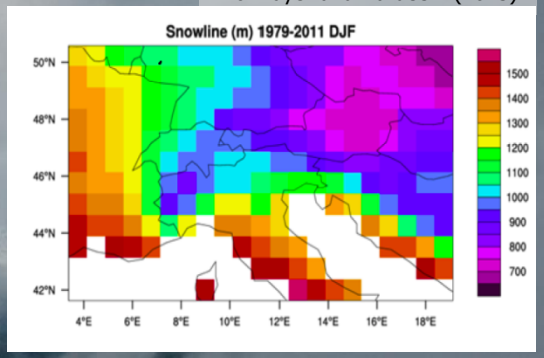
## Greater Alpine Region (GAR)

- 750.000 km$^2$ (~10% of Europe)
- 12 countries
- Covers the Alps, parts of the Balkan, the Apennine, the Ardeche, and the Cevennes
- Divided into 4 climatic sub-regions




Formayer and Nardeem (2013)




Formayer and Nardeem (2013)

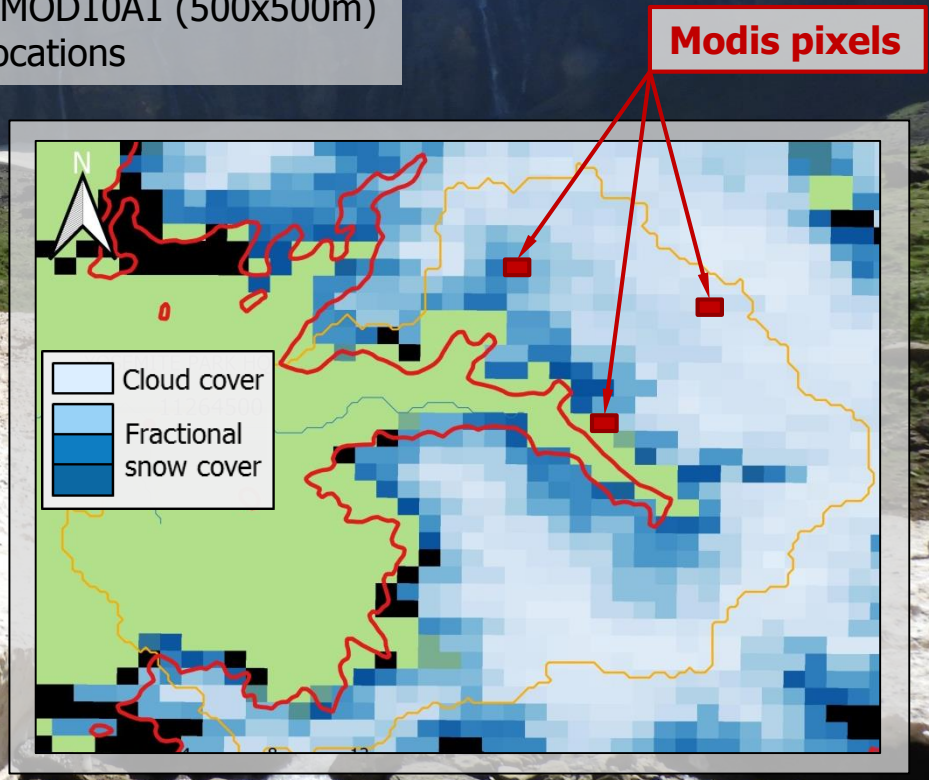
Objective:
Seamless, high-resolution analysis of regional differences in annual snow cover duration and their sensitivities to climatic drivers across the entire GAR

# Annual snow cover duration in GAR

## Regional snowline elevation method (RSLE)

Data to determine $D_{SC}$ (2000-2018, daily):
- Normalized difference snow index from Modis MOD10A1 (500x500m)
- In-situ observations of snow cover at ~2500 locations

What is the RSLE?
- **Spatial filter** to reduce cloud cover
- **Problem:** clouds can cover individual grid cells
- Exploits variability of cloud cover
- Assumes homogeneous snow line elevation over specified area ("tile") at any given time step
- The larger the tile, the lower the probability of no data due to cloud cover but the higher uncertainties in snow line elevations.



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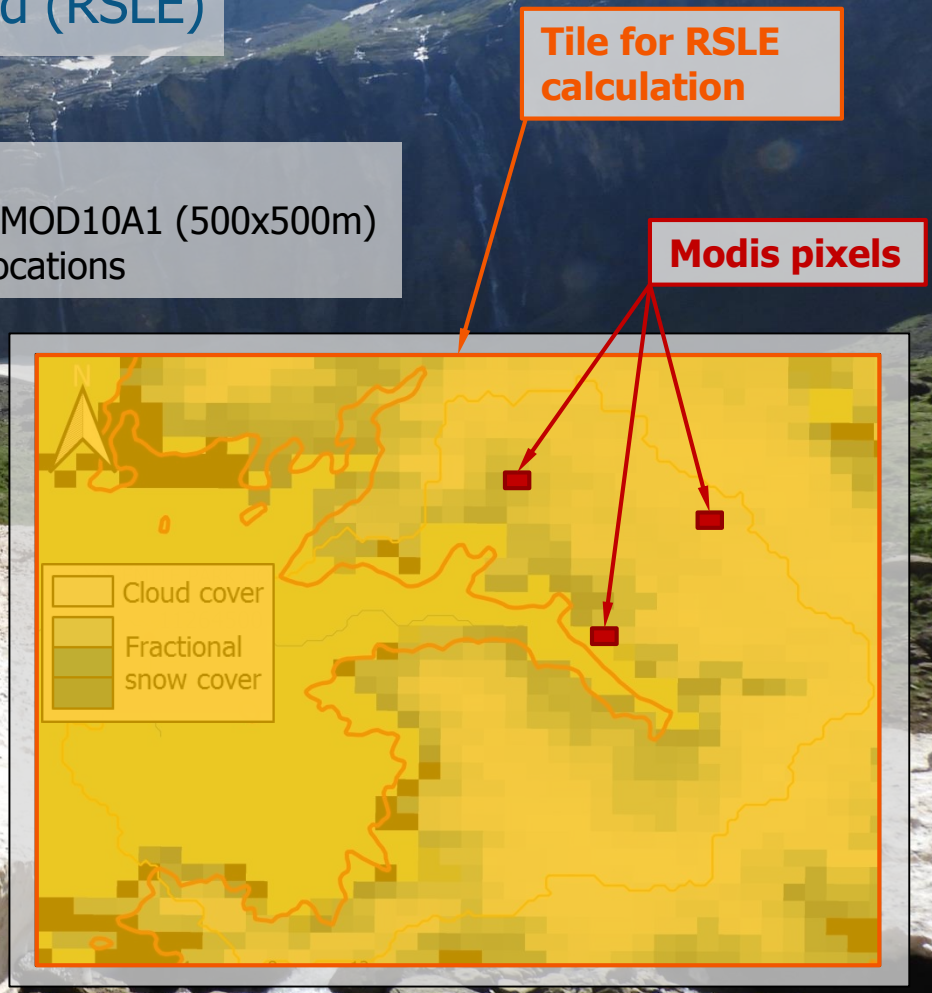


# Annual snow cover duration in GAR

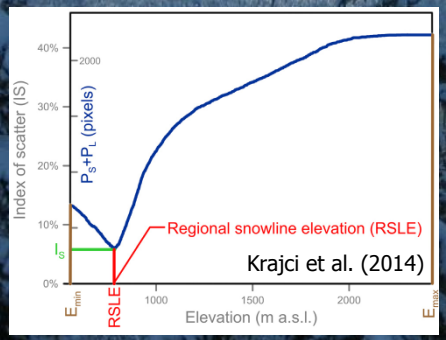
## Regional snowline elevation method (RSLE)

Estimate RSLE for each time step in each tile:

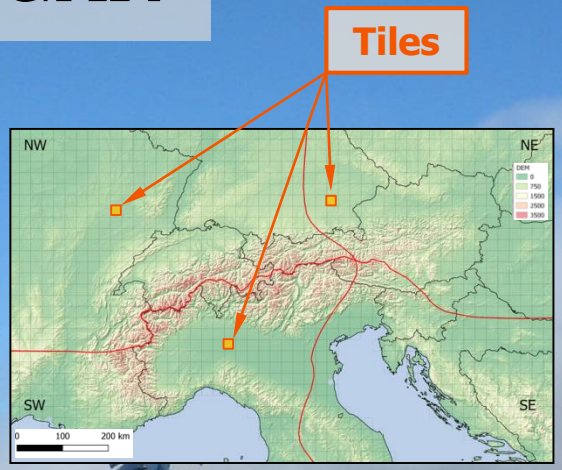
From all not cloud covered pixels within a tile calculate for each elevation:

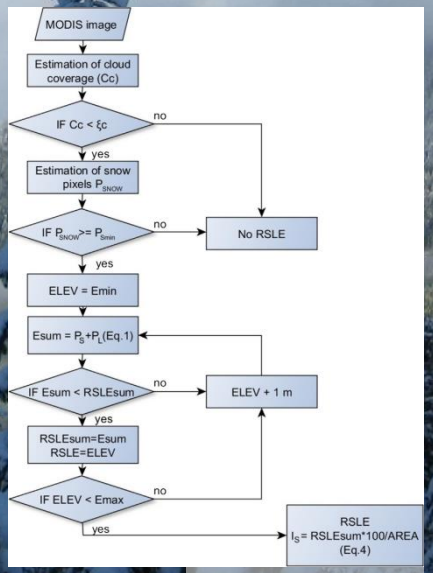
$$S_h(t) = P_{s,b,h}(t) + P_{l,a,h}(t)$$

$S_h$ is a scatter value at elevation h;
$P_{s,b,h}$ number of pixels with snow cover below elevation h
$P_{l,a,h}$ the number of no-snow pixels above elevation h.




For each time step RSLE is the elevation where $S_h \rightarrow min$

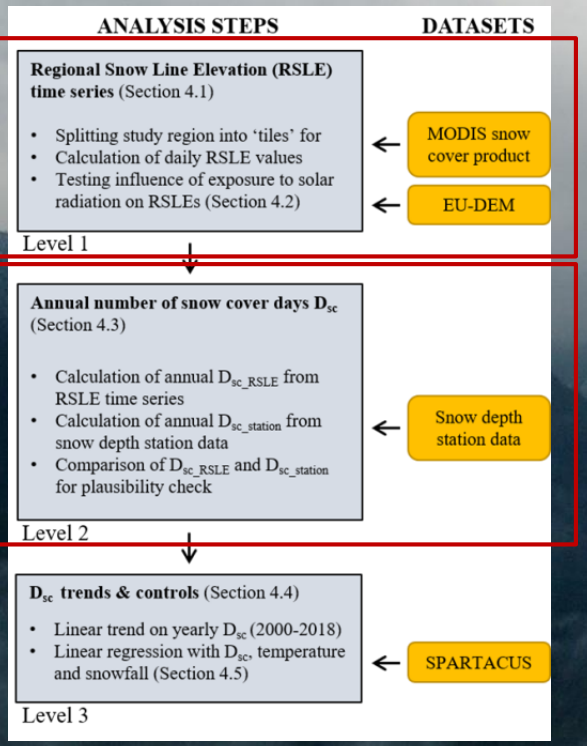


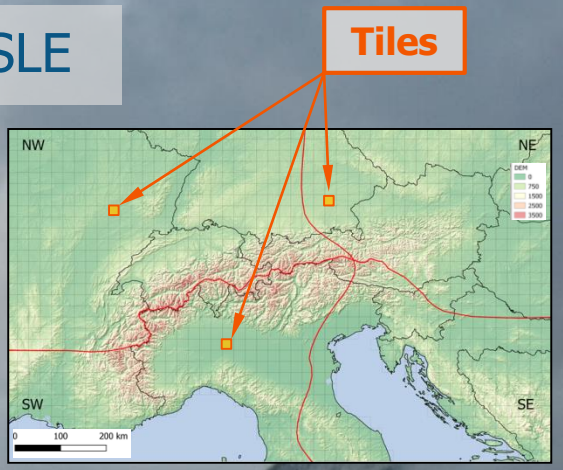

Krajci et al. (2014)

# Annual snow cover duration in GAR

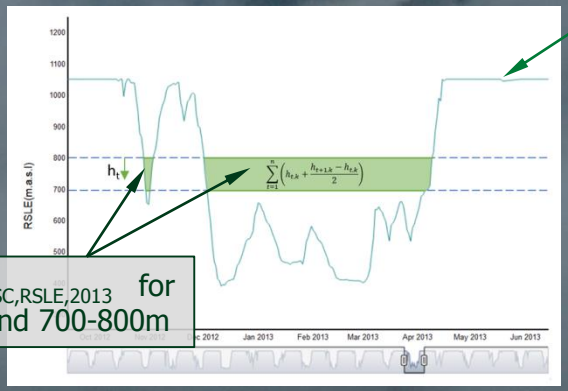
## Estimation of annual snow cover duration from RSLE




- Calculate RSLE time-series for each tile (25 x 25km$^2$)
- Calculate $D_{SC,RSLE}$ for each year in at each elevation in each tile from RSLE time-series
- Compare $D_{SC,RSLE}$ estimates to $D_{SC,station}$




RSLE time-series (2013) for one tile



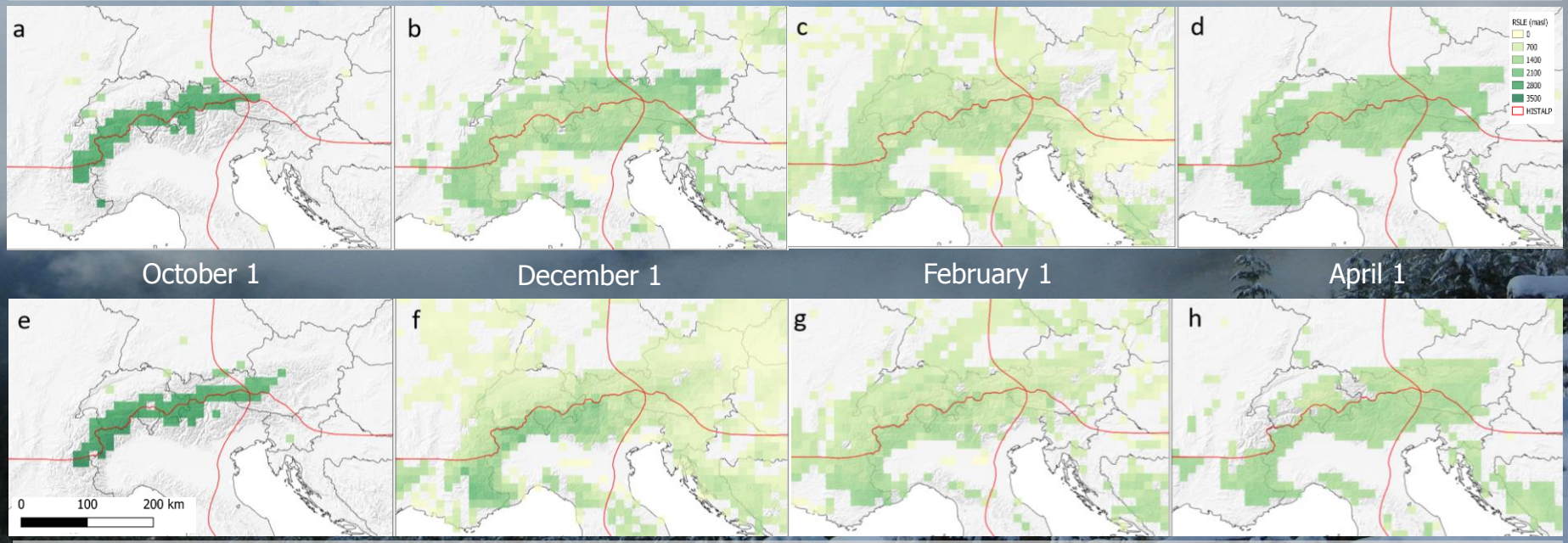

Average $D_{SC,RSLE,2013}$ for elevation band 700-800m

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional snow line elevation RSLE - snapshots

**Snow season 2000/2001**

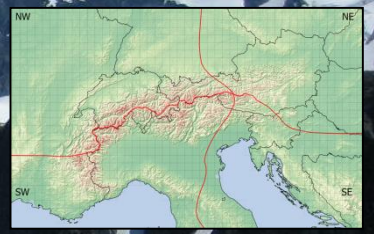


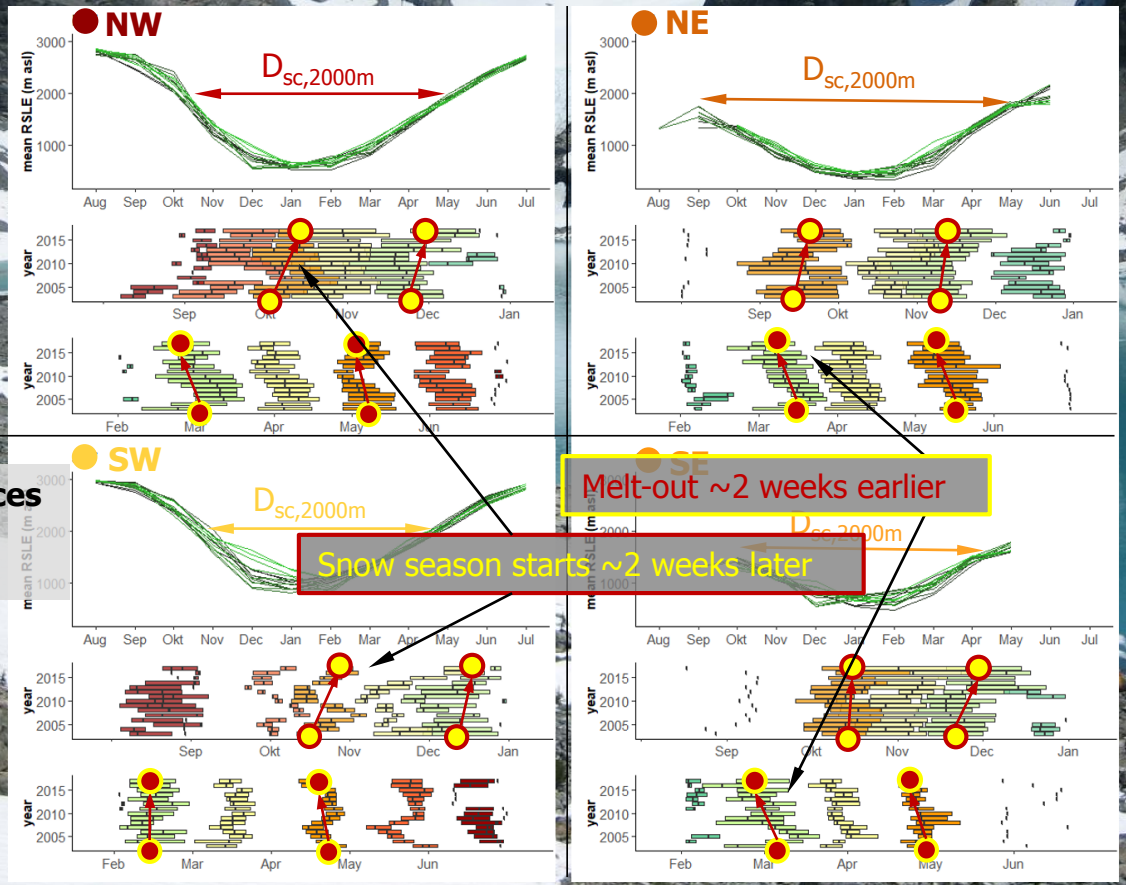

**Snow season 2017/18**

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional snow line elevation RSLE – temporal evolution



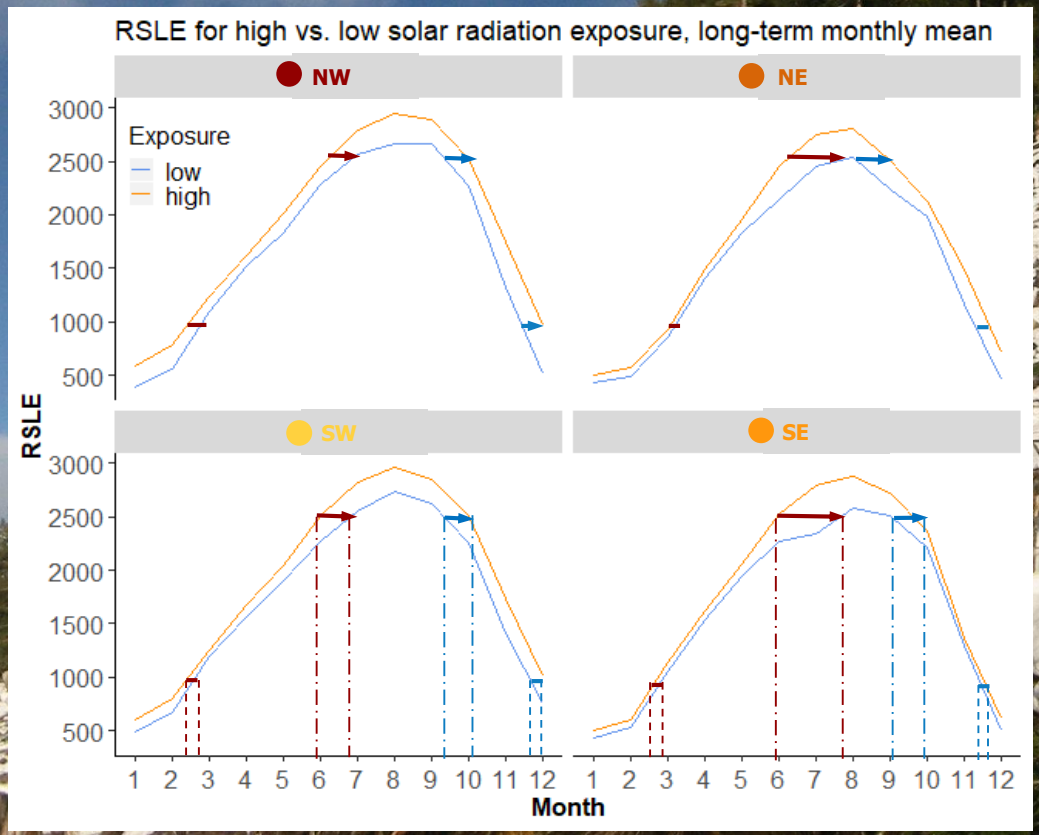


**Pronounced differences**
- **between elevations**
- **regions**

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional snow line elevation RSLE – influence of aspect





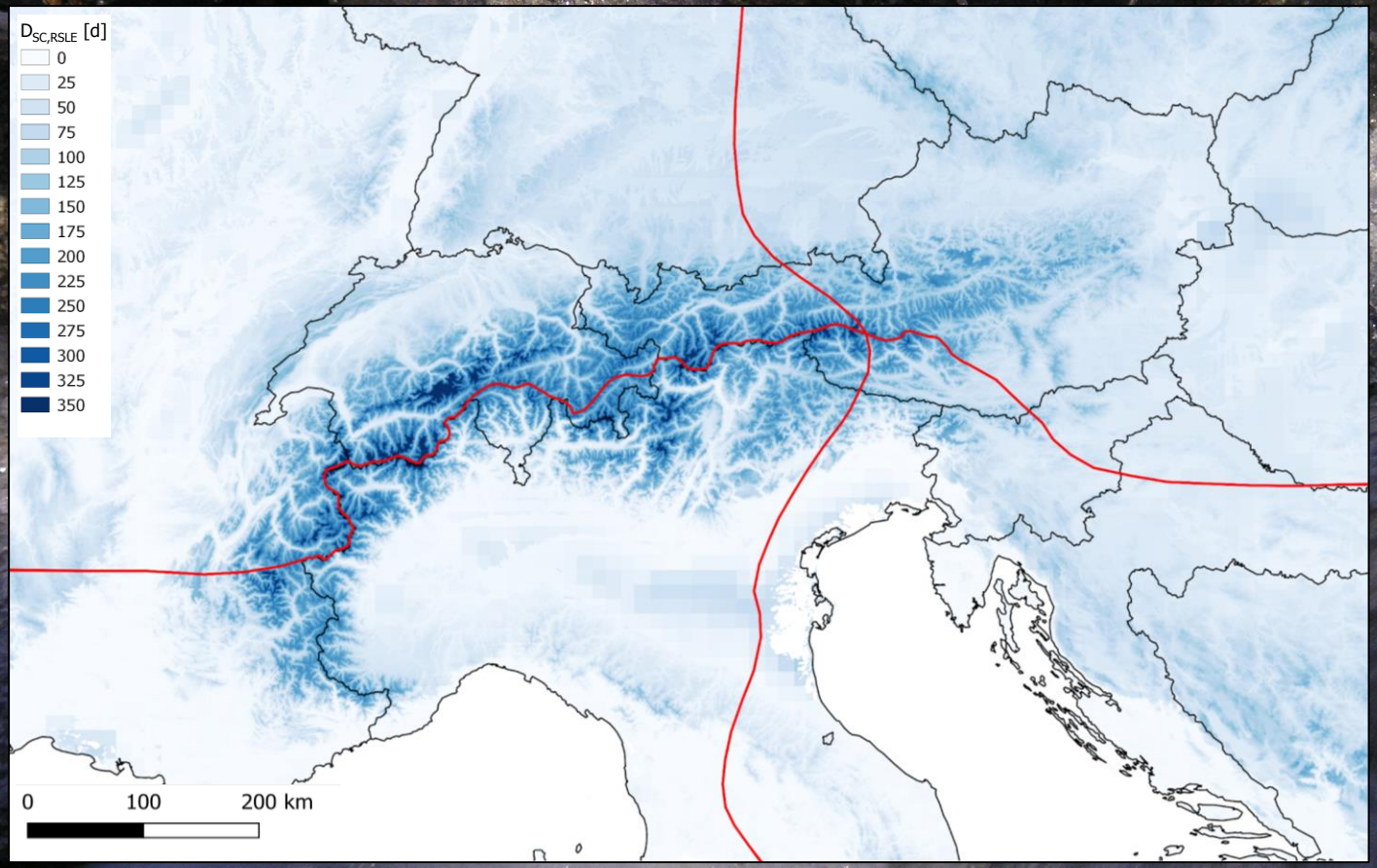
Low exposure locations (e.g. North aspect):

- Earlier start of snow accumulation (up to 3 weeks)
- Later melt-out (up to 4 weeks)
- Stronger differences at higher elevations

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

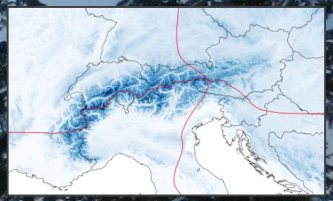
## Long-term mean annual snow cover duration $D_{SC,RSLE}$ (2000-2018)

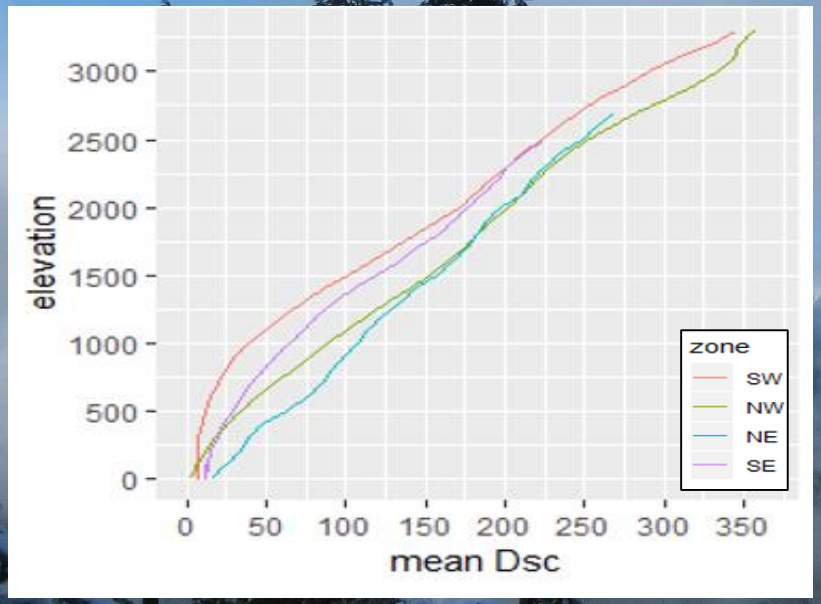


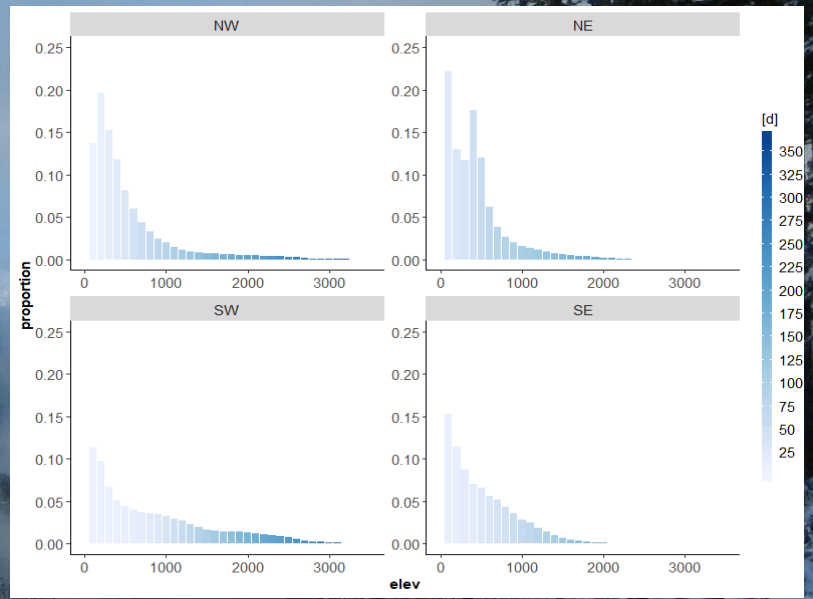

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional differences in $D_{SC,RSLE}$





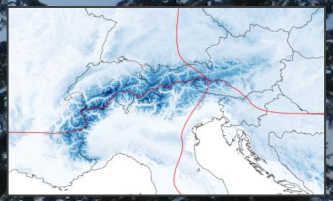

At same elevations

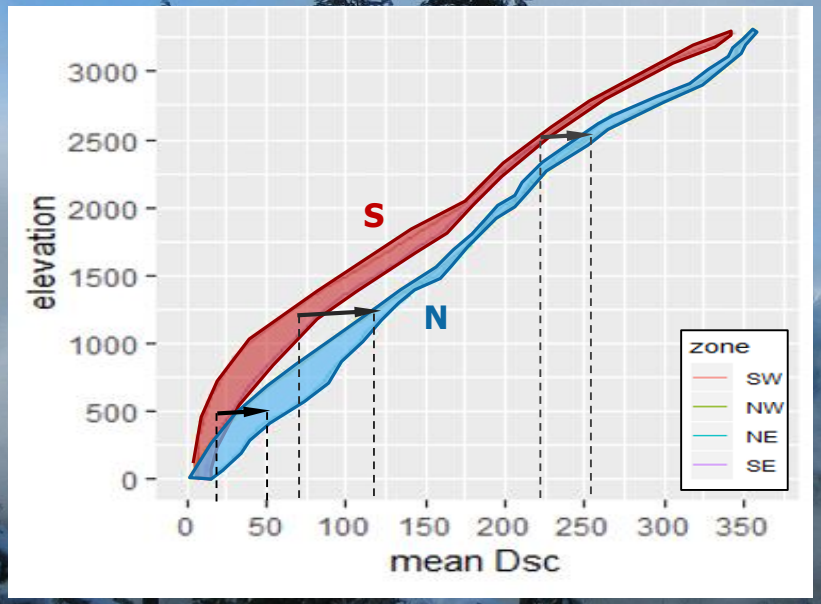
- $D_{SC,RSLE}$ 1-2 months longer in North
- $D_{SC,RSLE}$ <1 month longer in East

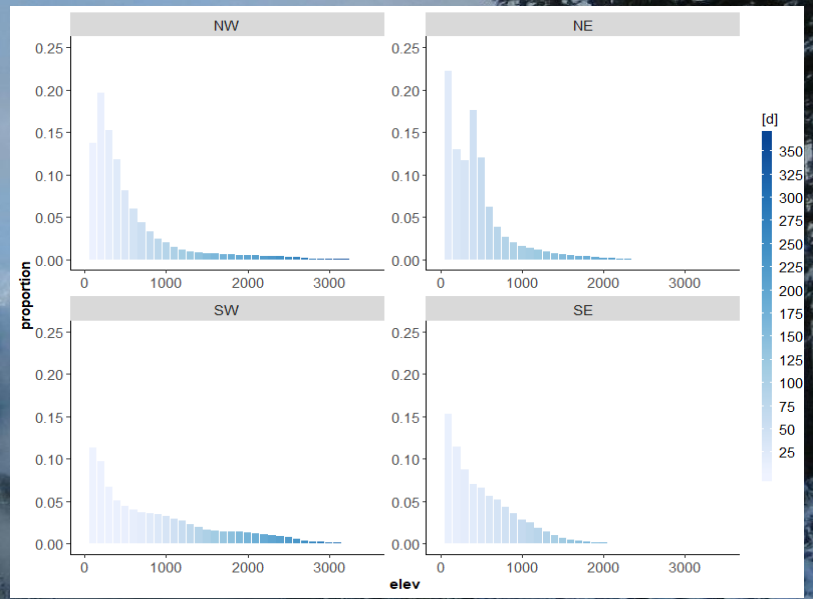
Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional differences in $D_{SC,RSLE}$





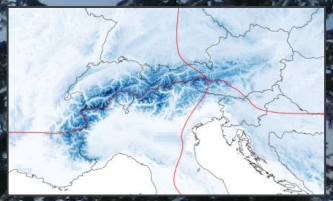

At same elevations

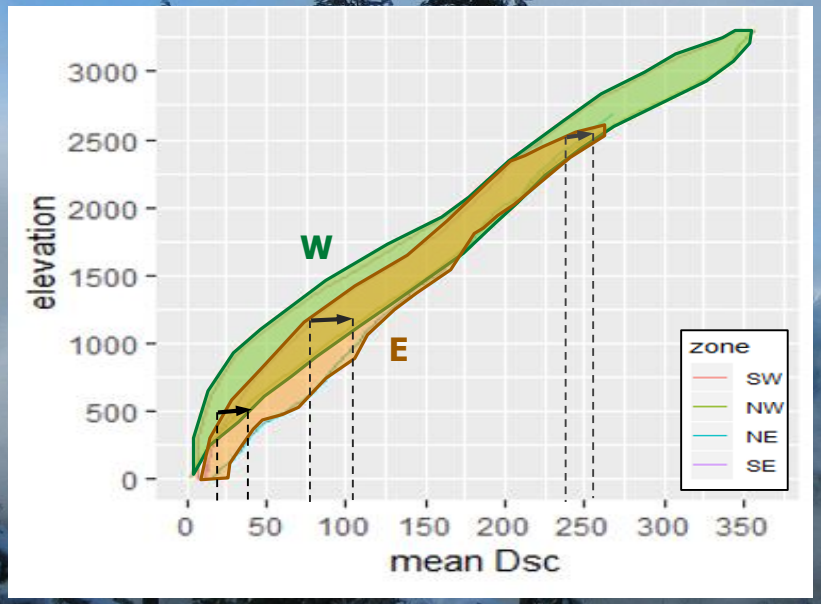
- $D_{SC,RSLE}$ 1-2 months longer in North
- $D_{SC,RSLE}$ <1 month longer in East

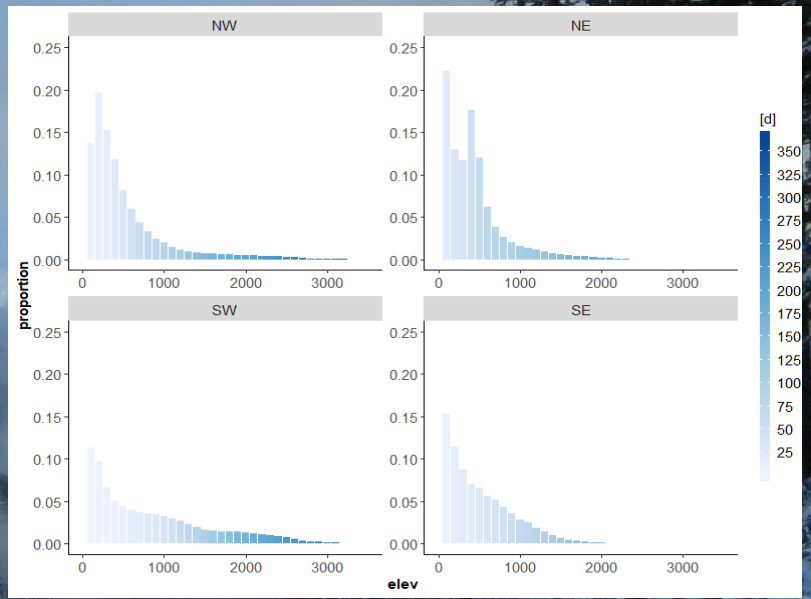
Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Regional differences in $D_{SC,RSLE}$





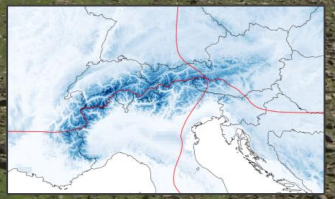

At same elevations

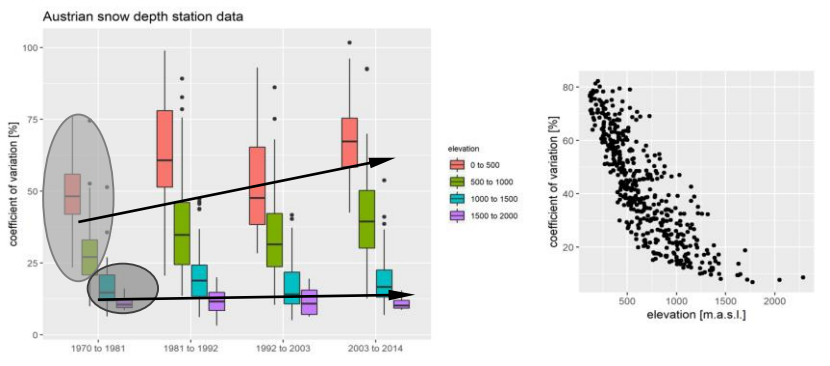
- $D_{SC,RSLE}$ 1-2 months longer in North
- $D_{SC,RSLE}$ <1 month longer in East

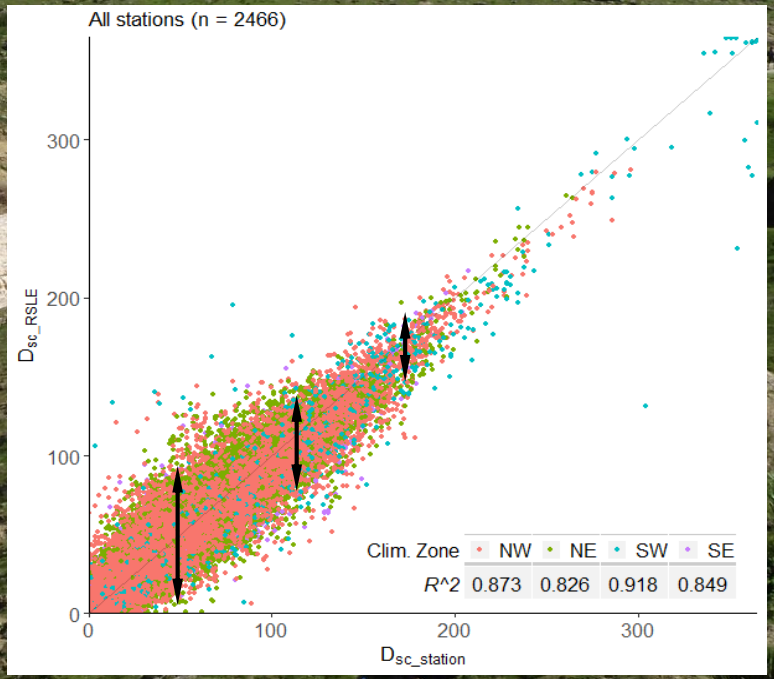
Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## $D_{SC,RSLE}$ vs. $D_{SC,station}$





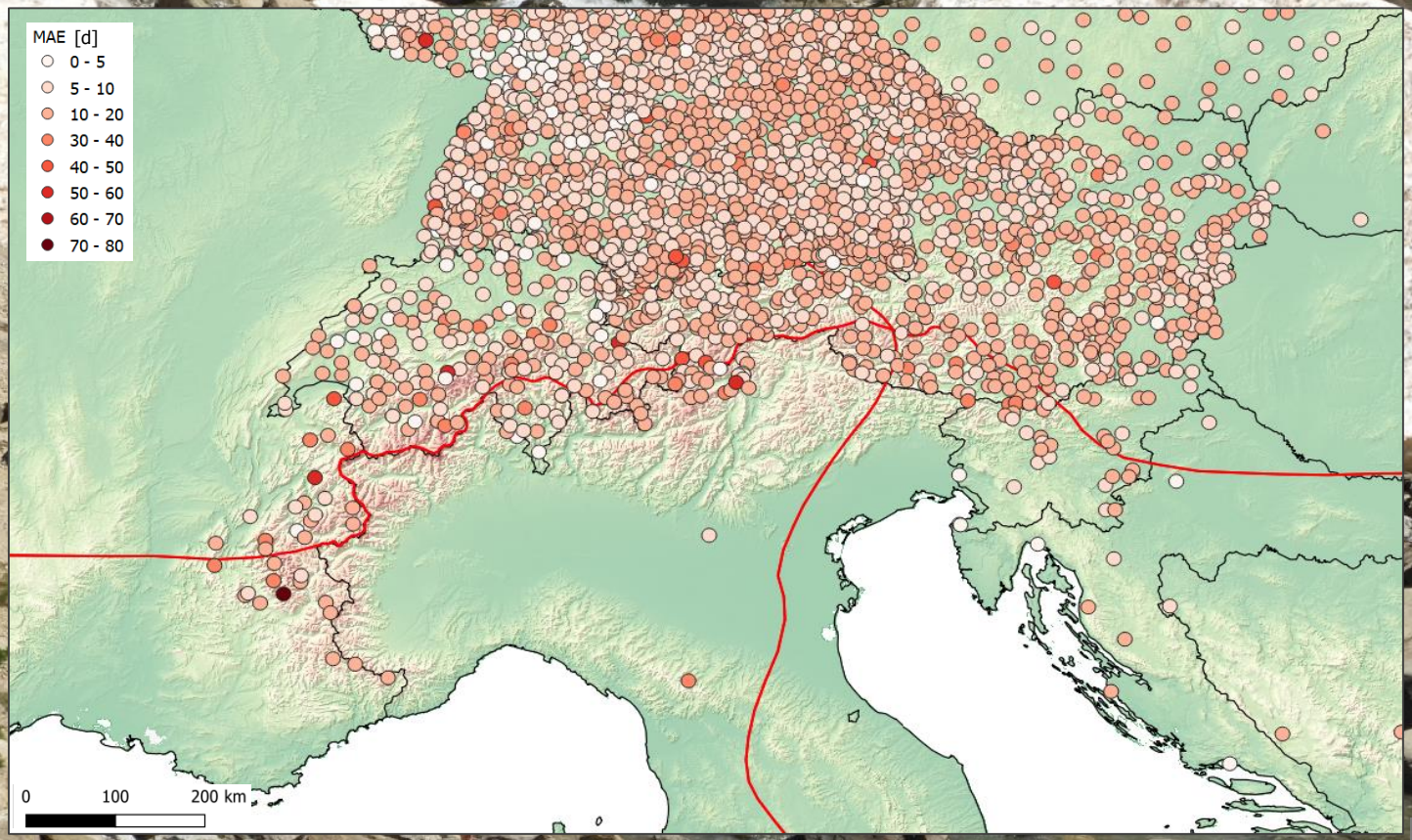




- Difference $D_{SC,RSLE}$ vs. $D_{SC,station}$ higher at low elevations
- $D_{SC}$ highly variable at low elevations, more stable at higher elevations
- Increase in low elevation $D_{SC}$ variability since 1970, stable at higher elevations

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

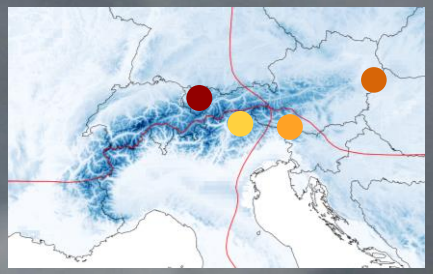
## $D_{SC,RSLE}$ vs. $D_{SC,station}$

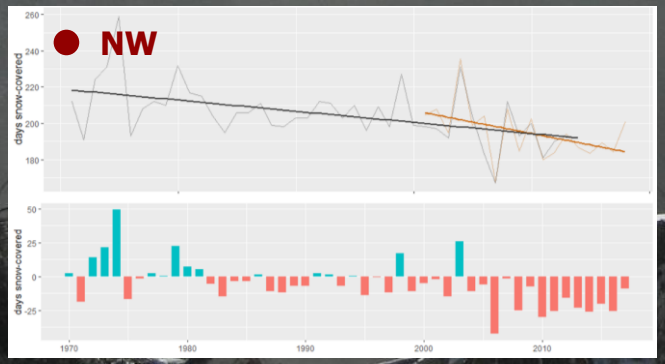


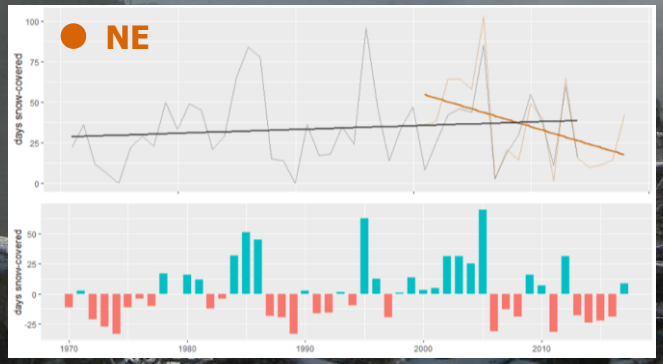

Fugger et al. (in prep.)

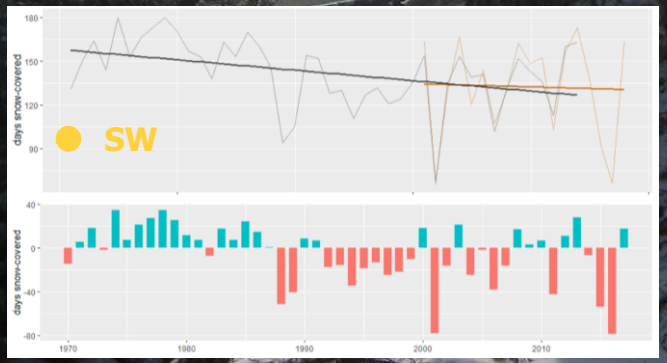
# Annual snow cover duration in GAR

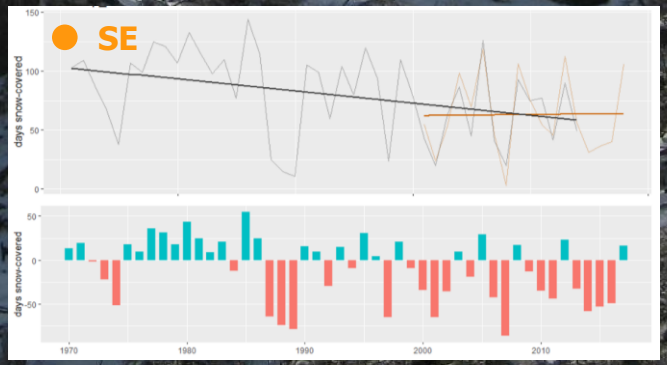
## Temporal trends in $D_{SC,RSLE}$ vs. $D_{SC,station}$





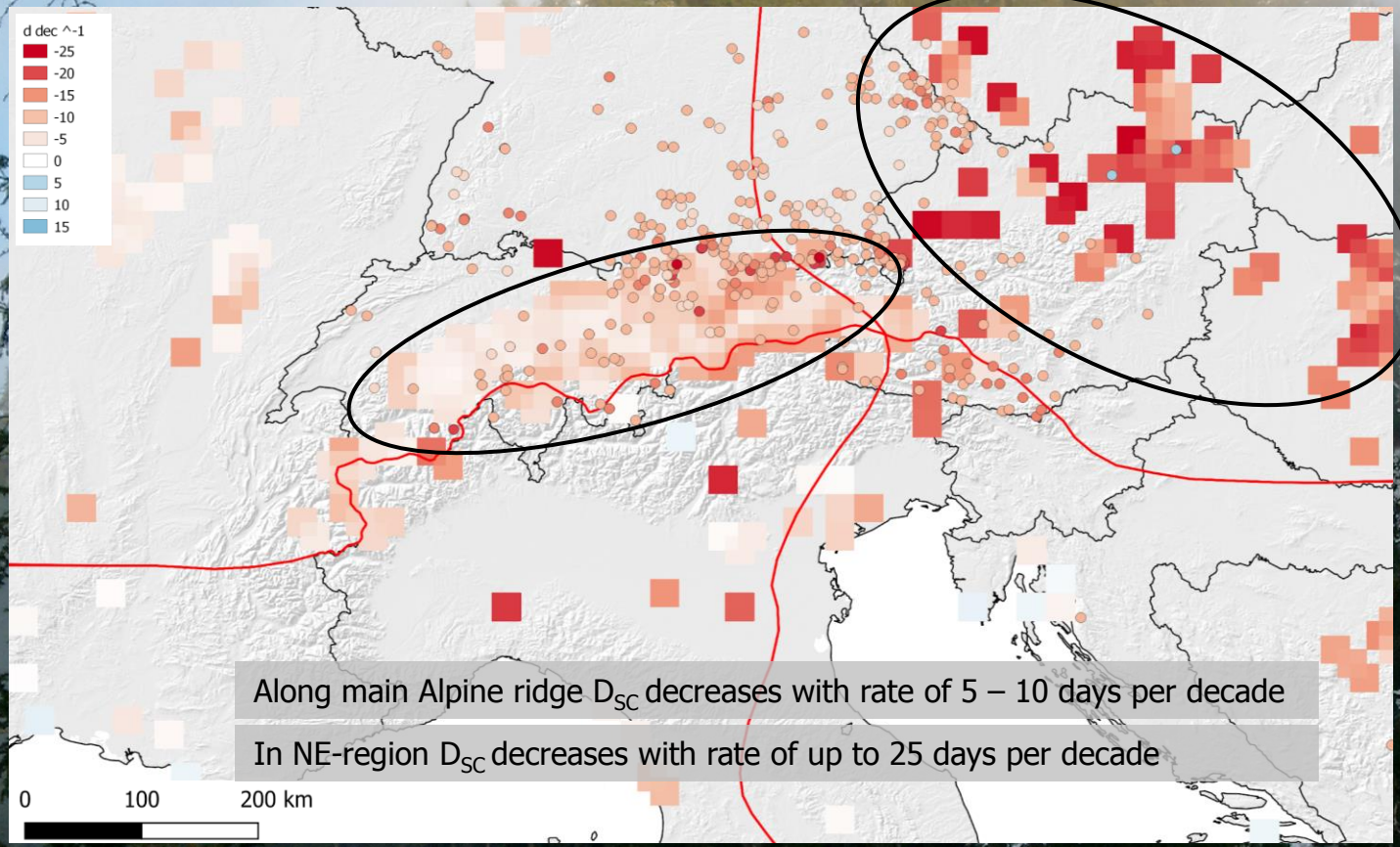




Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Temporal trends in $D_{SC,RSLE}$ vs. $D_{SC,station}$



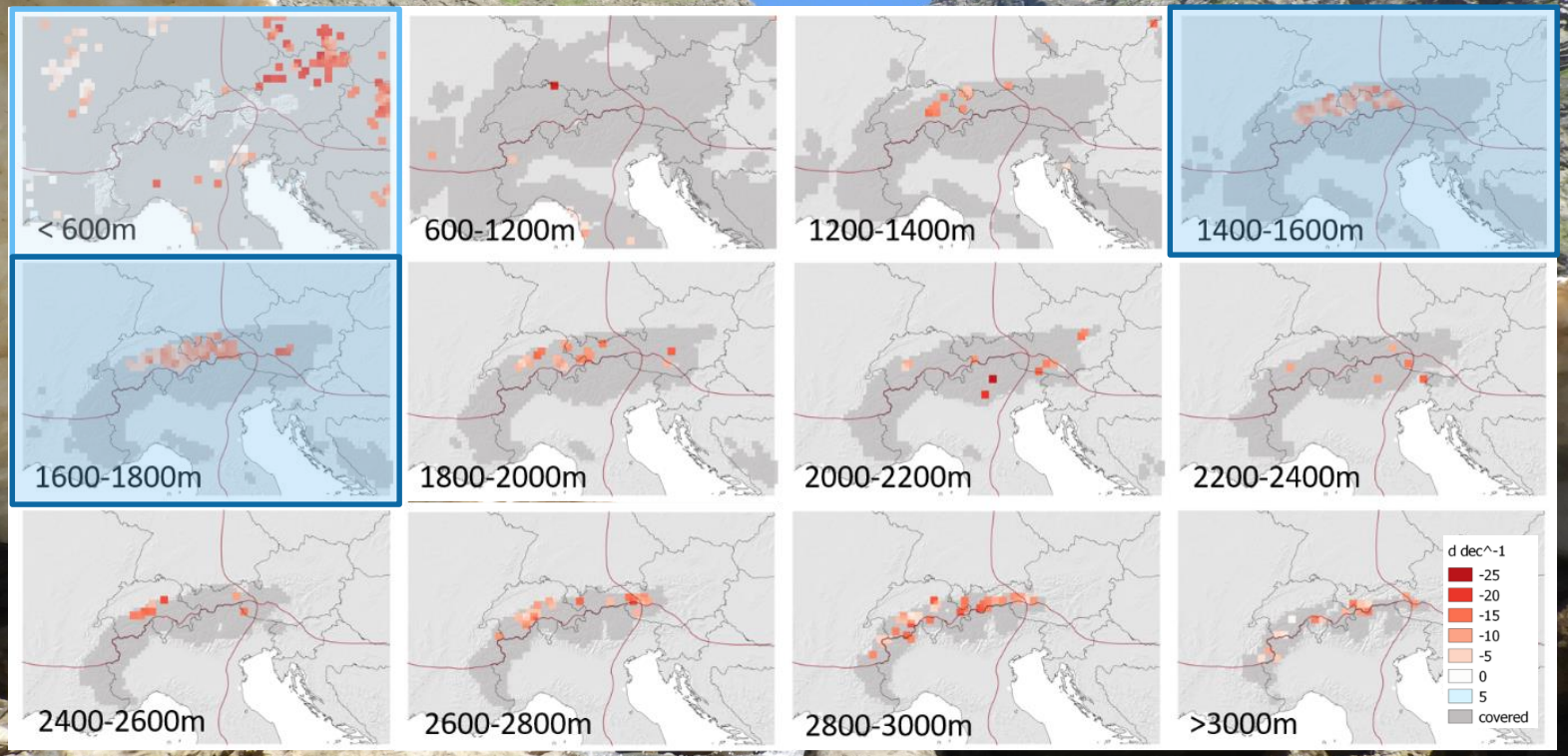

Along main Alpine ridge $D_{SC}$ decreases with rate of 5 – 10 days per decade

In NE-region $D_{SC}$ decreases with rate of up to 25 days per decade

Fugger et al. (in prep.)

# Annual snow cover duration in GAR

## Temporal trends in $D_{SC,RSLE}$ at different elevations




Low- and mid-elevation regions most sensitive to change

Fugger et al. (in prep.)

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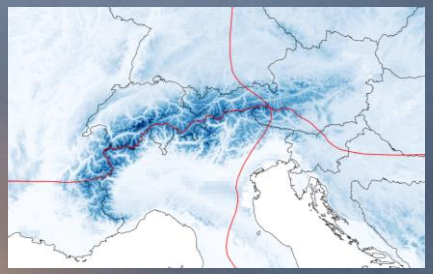

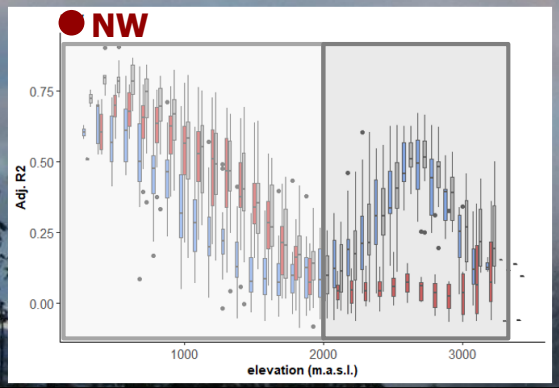


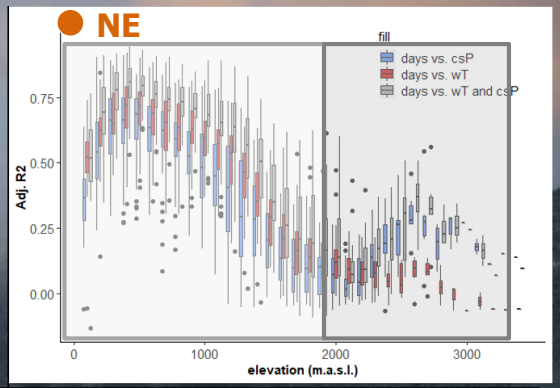


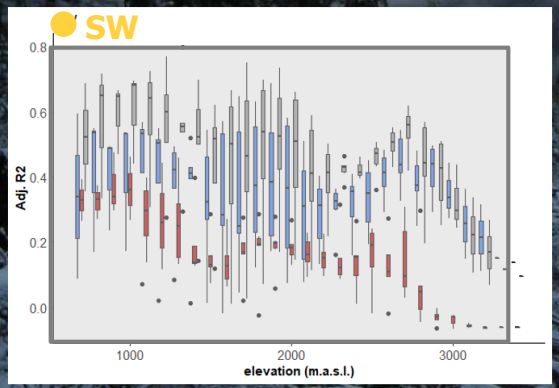


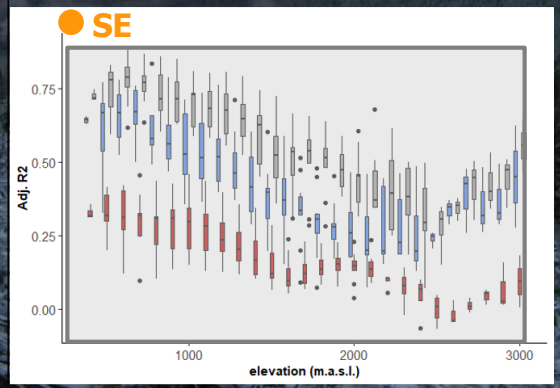


North:
- at low- to mid-elevations **temperature** dominant control on $D_{SC,RSLE}$
- at high-elevations **precipitation** dominant

South:
- **precipitation** dominant control on $D_{SC,RSLE}$ at all elevations

Fugger et al. (in prep.)


Thank you!