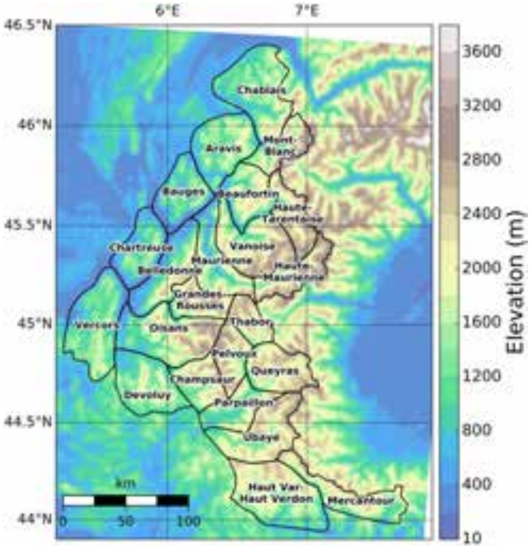
Elevation-dependent trends in extreme snow events in the French Alps from 1959 to 2019

Erwan Le Roux, Guillaume Evin, Nicolas Eckert, Juliette Blanchet, Samuel Morin

French Alps



Extreme snow events can:

- generate casualties & economic damages, e.g. roof collapse
- cause natural hazards (avalanche, winter storms)
- disrupt transportation, communication and electric systems

Credit: Ryan McFarland 2009. Collasped roof

Credit: TwinCities PioneerPress

Motivation:

- Determine **temporal trends in extreme** snow events for various areas (massifs, elevations) to adapt protective measures
- Understand the underlying causes of these trends

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Trends in extreme events for 2 snow metrics

We focus on:

- 1 meteorological metric: **snowfall**
- 1 snowpack metric: the **ground snow load** =the **snow load** of accumulated snow on the ground

<u>Meteorological metrics</u>

Precipitation (rainfall + **snowfall**) *in mm, same as kg m^{-2}*

snowfall

= solid precipitation (in kg m^{-2})

<u>Snowpack metrics</u>

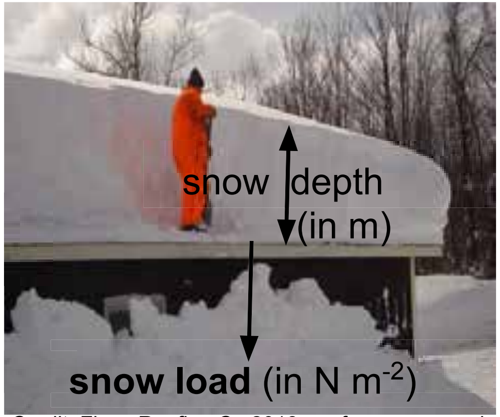
Snow depth *measured in m*

↓ x snow density, that vary from 100 to 800 kg m^{-3}

Snow water equivalent *measured in kg m^{-2}*

↓ x gravitational acceleration (g = 9,8 m s^{-2})

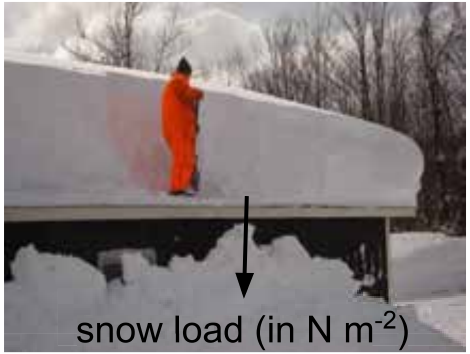
Snow Load *measured in N m^{-2}, same as Pa*



Credit: Flynn Roofing Co 2018. roof snow removal

Quick summary of the main trends

Based on the SAFRAN-Crocus reanalysis
*spanning the time period **1959-2019**,*
*and provided within **23 massifs in the French Alps**,* *<u>we find that:</u>*



Credit: Flynn Roofing Co 2018. roof snow removal

snowfall
= solid precipitation (in kg m^{-2})

Extreme ground snow load (snow load on the ground) are

- **stationary** or **decreasing** above 900 m (depending on locations)
- **exceeding roof standards** in 2019 for half massifs at 1800 m

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Extreme snowfall are

- mainly **decreasing** or **stationary** below 1000 m of elevation
- both **increasing** and **decreasing** (depending on locations) for intermediate elevations, i.e. between 1000 m and 3000 m
- mainly **increasing** or **stationary** above 3000 m of elevation

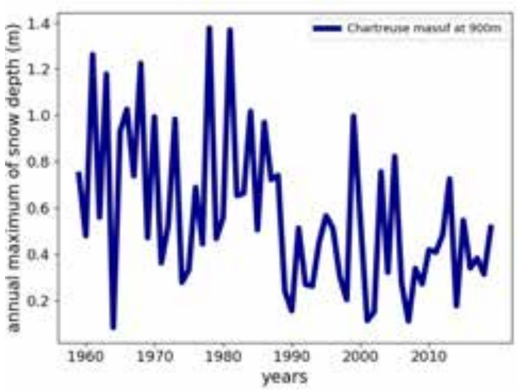
Work in progress

Statistical Methodology

Trends in time series of annual maxima

<u>Input:</u> a **time series** of **annual maxima**

<u>Motivation:</u> Determine **temporal trends** in such time serie. Is it increasing ? decreasing ? stationary ?

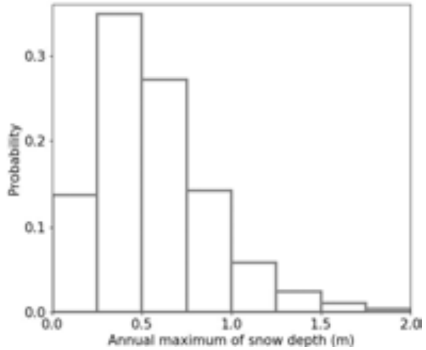


Example of a time series of **annual maxima**

The standard probability **distribution for annual maxima** is the Generalized Extreme Value (GEV) distribution (Coles, 2001) with **3 parameters**: the **location** (≃ the average), the **scale** (≃ the standard deviation), the shape.

Stationary model

The 3 **parameters** of the GEV distribution **do not change with time**. We find: location = 0.42 m scale = 0.25 m, shape = 0.04



The **GEV distribution** fitted on the time series

Non-stationary model

Some **parameters** of the GEV distribution of annual maxima **change with time**:

- The **location** parameter can decrease/increase **linearly with time** = less/more intense maxima in average = the histogram shifts to the left/right
- The **scale** parameter can decrease/increase **linearly with time** = less/more variance for the maxima = the histogram shrinks/spreads

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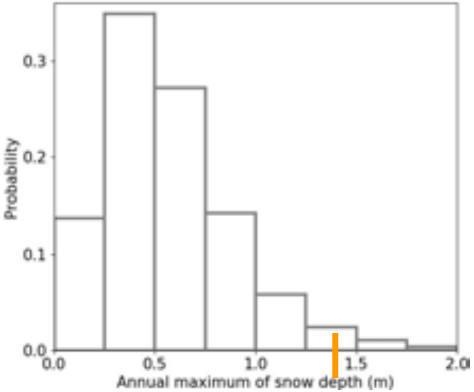
Statistical Methodology

“Extreme” is defined as a return level

Output: **50-year return level**
The quantity exceeded one time out of 50 times in average, which equals the quantile 0.98 = 49/50



49 times out of 50 in average

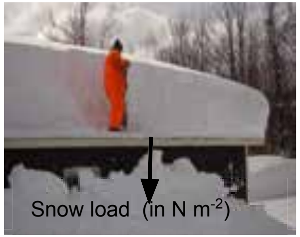
one time out of 50 in average

Stationary return-level

The return level stays the same with time because the histogram stays the same with time

Non-stationary return-level

The return level changes with time because the histogram changes with time



Credit: Flynn Roofing Co 2018.
roof snow removal

Snowfall
= solid precipitation (in mm)

Examples of applications:

Extreme ground snow load
We study **50-year return levels** because this is the level considered by French structure standards, to build roofs of structures

Extreme snowfall
We study **100-year return levels** because this is the level considered to build avalanche protections

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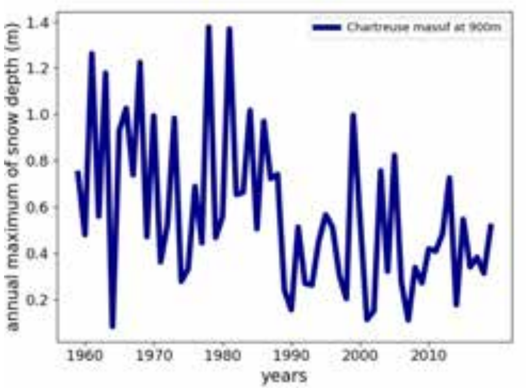
Statistical Methodology

Workflow for each time series of annual maxima

Input: a **time series** of **annual maxima**



Example of a time series of **annual maxima**

Workflow:

We consider several models (stationary and non-stationary)

1) Estimation. Parameters of each model are estimated with the maximum likelihood method and goodness-of-fit is checked

2) Selection. We select the model that minimizes an information criterion, i.e. that

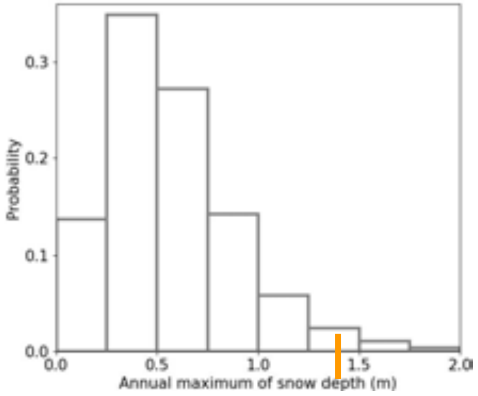
- explains well the observations
- has few parameters

3) Significance. If the selected model is non-stationary, its significance is assessed with a likelihood ratio test.

Output: **50-year return level**

The quantity exceeded one time out of 50 times in average

and potential trends in 50-year return level



49 times out of 50 in average

one time out of 50 in average

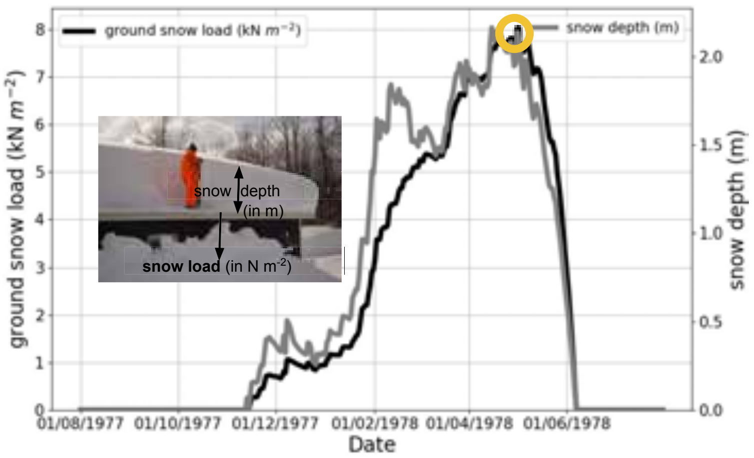
Result 1. Trends in 50-year return level of ground snow load

Data. Annual maxima of ground snow load

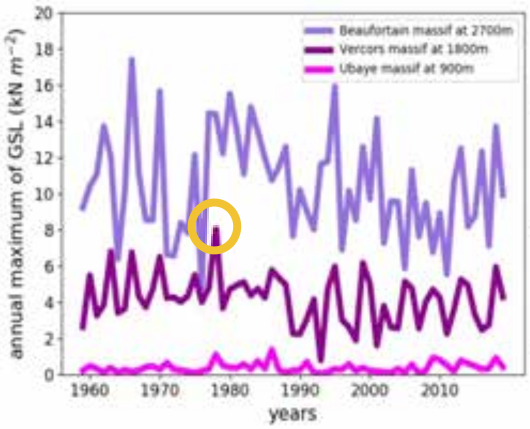
1) Every 300 m of altitude, for each massif, and each year (from August to July) **we extract the annual maximum**

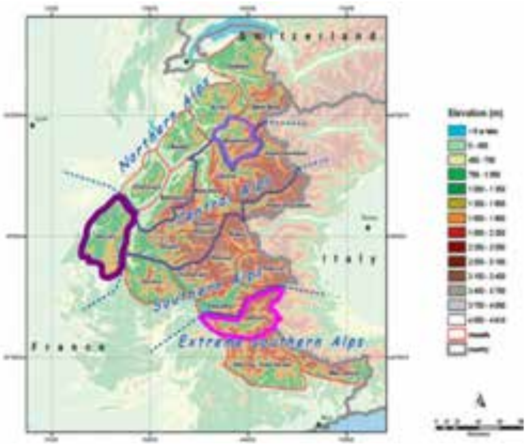
2) Every 300 m of altitude, for each massif, we have a time series of **annual maxima** of ground snow load (GSL) from 1959 to 2019

3) For each time series, we apply our methodology, to finally obtain 50-year return levels and potential trends in 50-year return levels



ground snow load & snow depth in 1978
for the Vercors massif at 1800 m





Three examples of time series of annual maxima of ground snow load (GSL) from 1959 to 2019
for the Ubaye massif at 900 m, for the Vercors massif at 1800 m, and for the Beaufortain massif at 2700 m

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Result 1. Trends in 50-year return level of ground snow load

Elevation-dependency of trends

We study the relative change between 1960 and 2010 for the **50-year return level** of ground snow load (GSL)

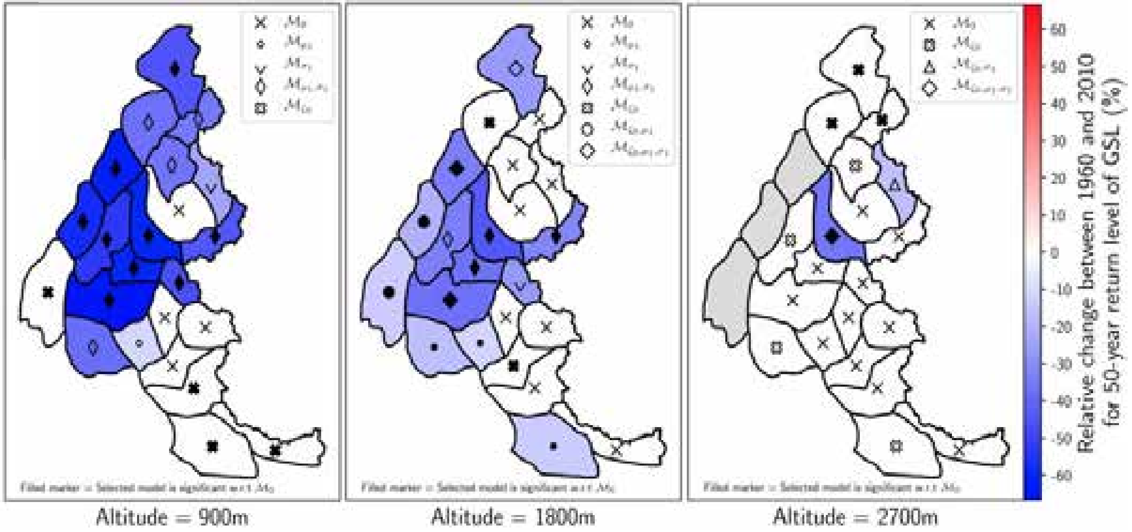
Above 900 m we find either

- a **decrease** (non stationary model)
- no trends (stationary model)

The decrease in snow load hazard is:

- Mainly located in the Northwest
- Less important for higher altitudes

The largest **decrease** is found at 900m with −30% on average for 50-year return levels



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Result 1. Trends in 50-year return level of ground snow load

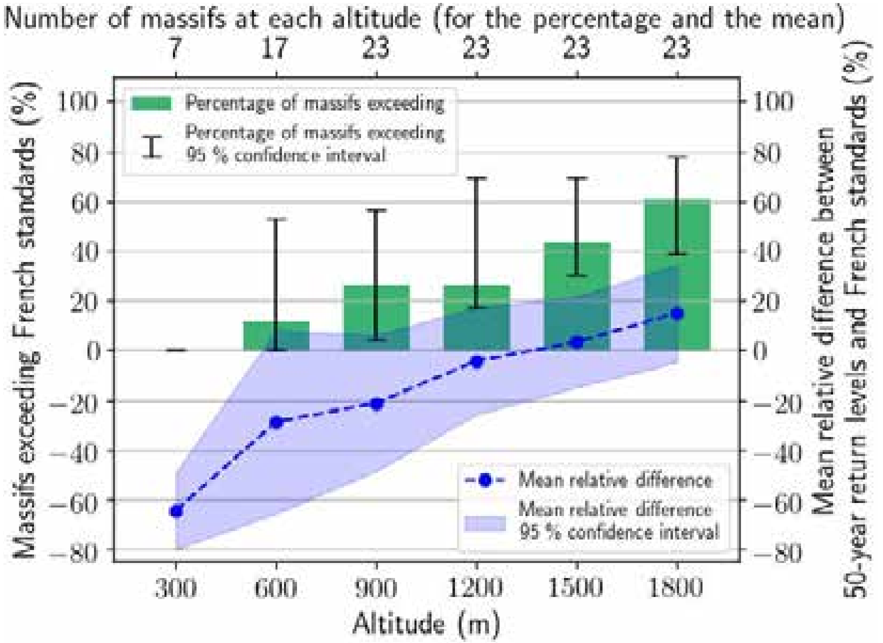
Comparison with French structure standards

We compare our 50-year return level in 2019 with 50-year return level from French structure standards

- the **percentage of massifs where our result exceeds French standards** increase with the altitude, reaching more than **half massifs at 1800 m**
- the **mean relative difference** between our results and French standards is positive above 1500 m

In our NHESS article, we also show that:

These exceedances are likely because **French standards were devised with** ground snow load (GSL) estimated from snow depth maxima and **constant snow density equal to 150 kg m^{-3}** which underestimate typical density values for the snowpack



If we do not account for the decreasing trends, our result exceeds French standards for **half massifs at 900 m, 1200 m, 1500 m and 1800 m**

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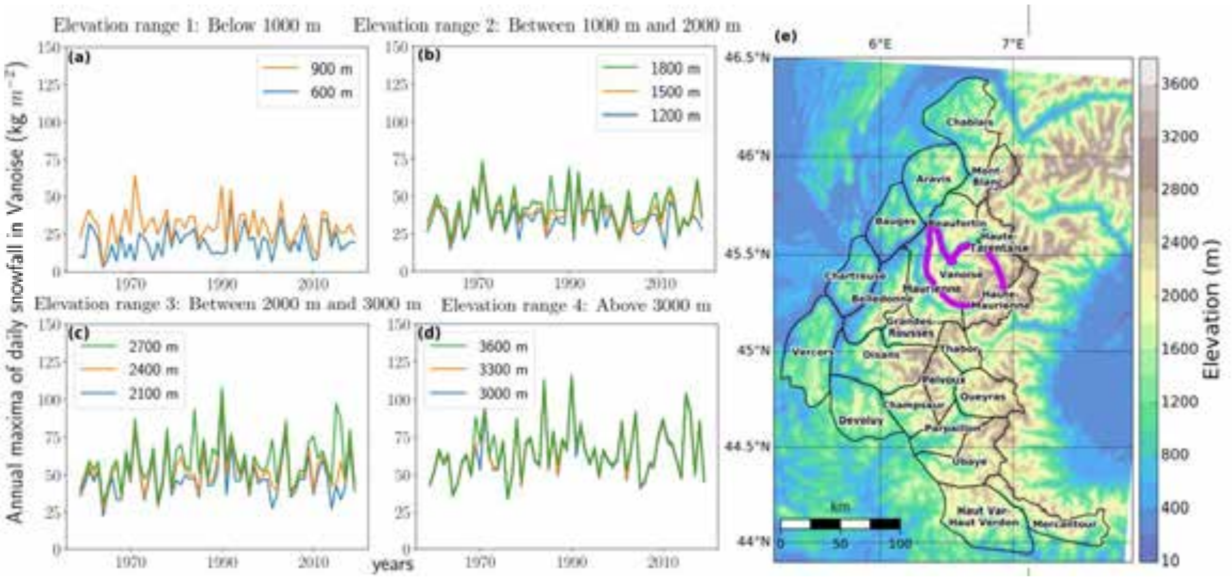
Result 2. Trends in 100-year return level of snowfall

Data. Annual maxima of daily snowfall

Time series of annual maxima of daily **snowfall** are clustered into **four ranges of elevations** (see Figure for an example for the Vanoise massif = **purple region**)

Snowfall
= solid precipitation (in mm)

1. Below 1000 m
2. Between 1000 m and 2000 m
3. Between 2000 m and 3000 m
4. Above 3000 m



For **each massif, and each range** of elevations we apply the **same workflow**: Estimation/Selection/Significance to finally obtain **50-year return level** and potential trends in 50-year return level

The main methodological difference with Result 1 is:
Result 1: each model was fitted on a **single** time series.
Result 2: each model is fitted on **several** time series (all times series from the elevation range).
→This reduces the uncertainty in return levels

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Result 2. Trends in 100-year return level of snowfall

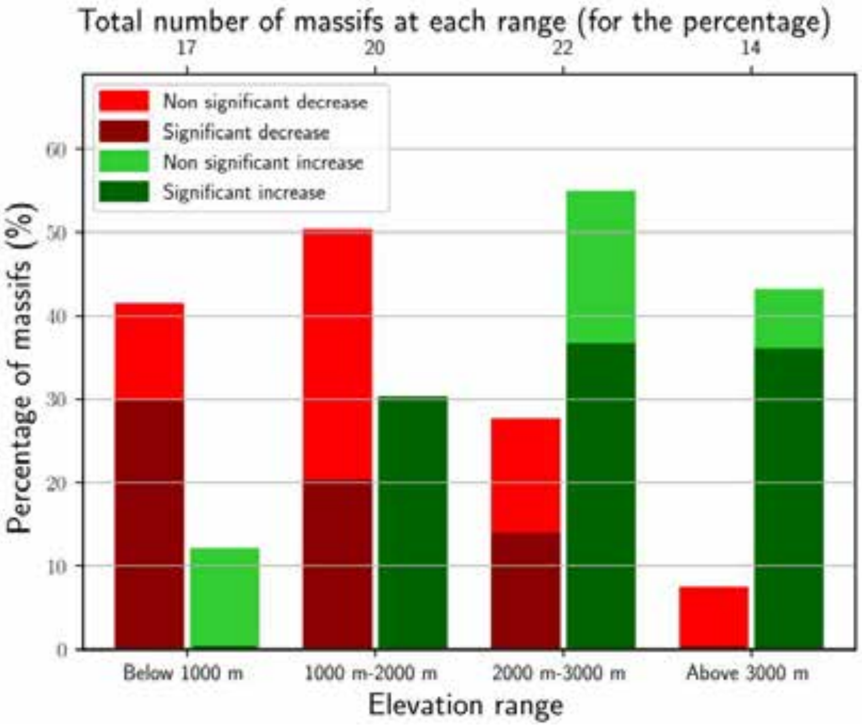
Elevation-dependent trends

Temporal trends in **100-year return level** of daily snowfall are

- mainly **decreasing** (40 %) or **stationary** (45 %) below 1000 m

- both **increasing** (40 %) and **decreasing** (40 %) for intermediate elevations, i.e. between 1000 m and 3000 m.

- mainly **increasing** (40 %) or **stationary** (50 %) above 3000 m



Result 1. Trends in 100-year return level of snowfall

Elevation-dependent trends

We study the **relative change** between 1959 and 2019 for the **100-year return level of snowfall**.

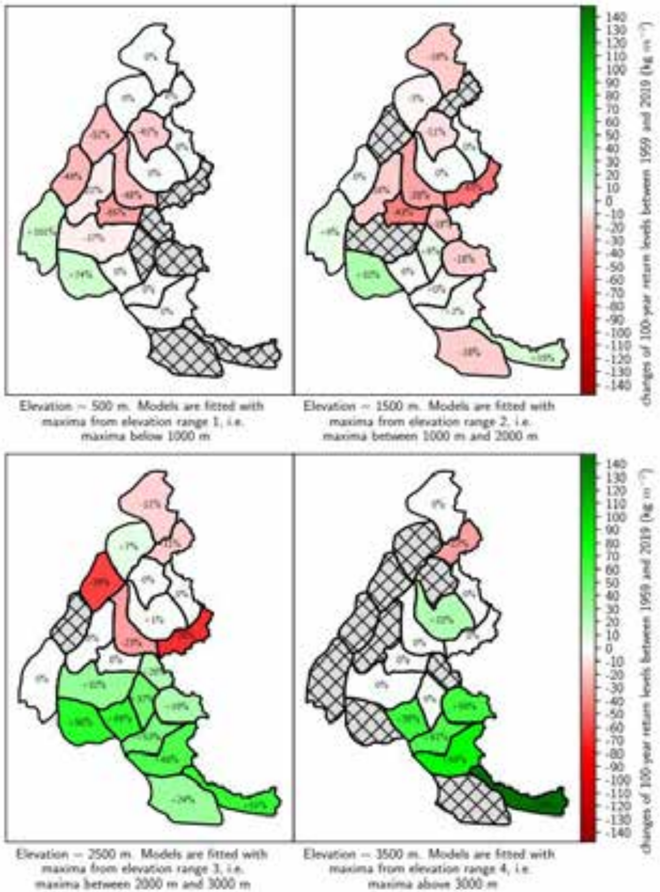
Below 2000 m,

- on average we find ≃**-7%** for the last 60 years
- a majority of **decrease** are observed in the **North**

Above 2000 m,

- on average we find ≃**+20%** for the last 60 years
- At 2500 m, we observe a **contrasted pattern**: **decreasing** trend in the north of the French Alps while we observe **increasing** trend in the south.

We believe, this pattern might be due to **increasing** trends in extreme snowfall at the proximity of the Mediterranean Sea.



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Summary of the main trends

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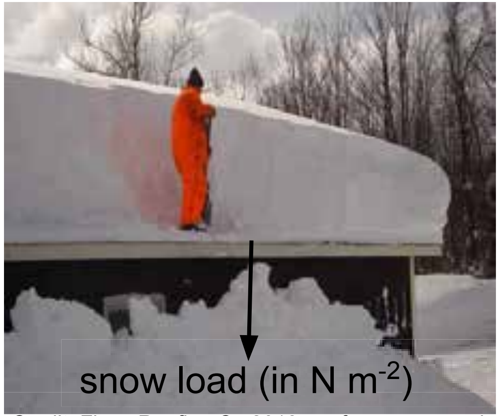

Credit: Flynn Roofing Co 2018. roof snow removal

Temporal in 50-year return level of ground snow load (snow load on the ground) are

- **stationary** or **decreasing** above 900 m (depending on locations)
- **exceeding roof standards** for half massifs at 1800 m

Non-stationary extreme value analysis of ground snow loads in the French Alps: a comparison with building standards

Erwan Le Roux[1], Guillaume Evin[1], Nicolas Eckert[1], Juliette Blanchet[2], and Samuel Morin[3]

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snowfall
= solid precipitation (in kg m^{-2})

Temporal trends in 100-year return level of daily snowfall are

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- mainly **increasing** or **stationary** above 3000 m of elevation

Work in progress

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