Climate change risks related to the shrinkage of the mountain cryosphere: state of the art and challenges for statistical modelling

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Weather Extremes and Climate Change
19 January 2022

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Context, concepts and guidelines

Glaciers and glacier risks

Snow extremes and related risks

Snow avalanche risk

Take home message

Mountain environments

- Strong physical constraints and extreme conditions: steep slopes, thaw-frost, intense precipitation, etc.
- Importance of the cryosphere: snow, ice/glaciers, permafrost.
- High attractiveness for tourism and permanent human settlements vs. lack of space: real estate pressure.
- Remarkable / fragile socio-environmental systems.
- “Small” research communities.

Chamonix valley, French Alps, winter and summer views.

Specific hazards / risks

- Specific phenomena driven by physical constraints.
- Deep socio-economic consequences when interacting with elements at risk: risk for settlements, people, critical infrastructures (incl. road viability and accessibility losses).

Rockfall ©Tareom.com

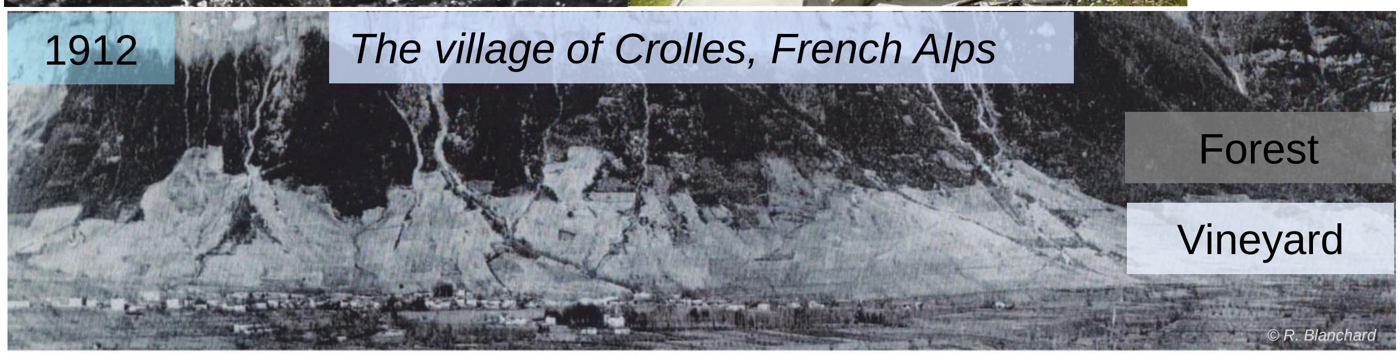
Snow storm and drifting snow © INRAE ETNA

Avalanche deposit on a dwelling house © INRAE ETNA

Debris flow deposit on road © INRAE ETNA

Systems and risks changing faster than ever

- Fast warming modifying physical characteristics dramatically.
- Exacerbated societal mutations and land cover changes.
- Risk highly non-stationary in all its components.



Main recent settlements

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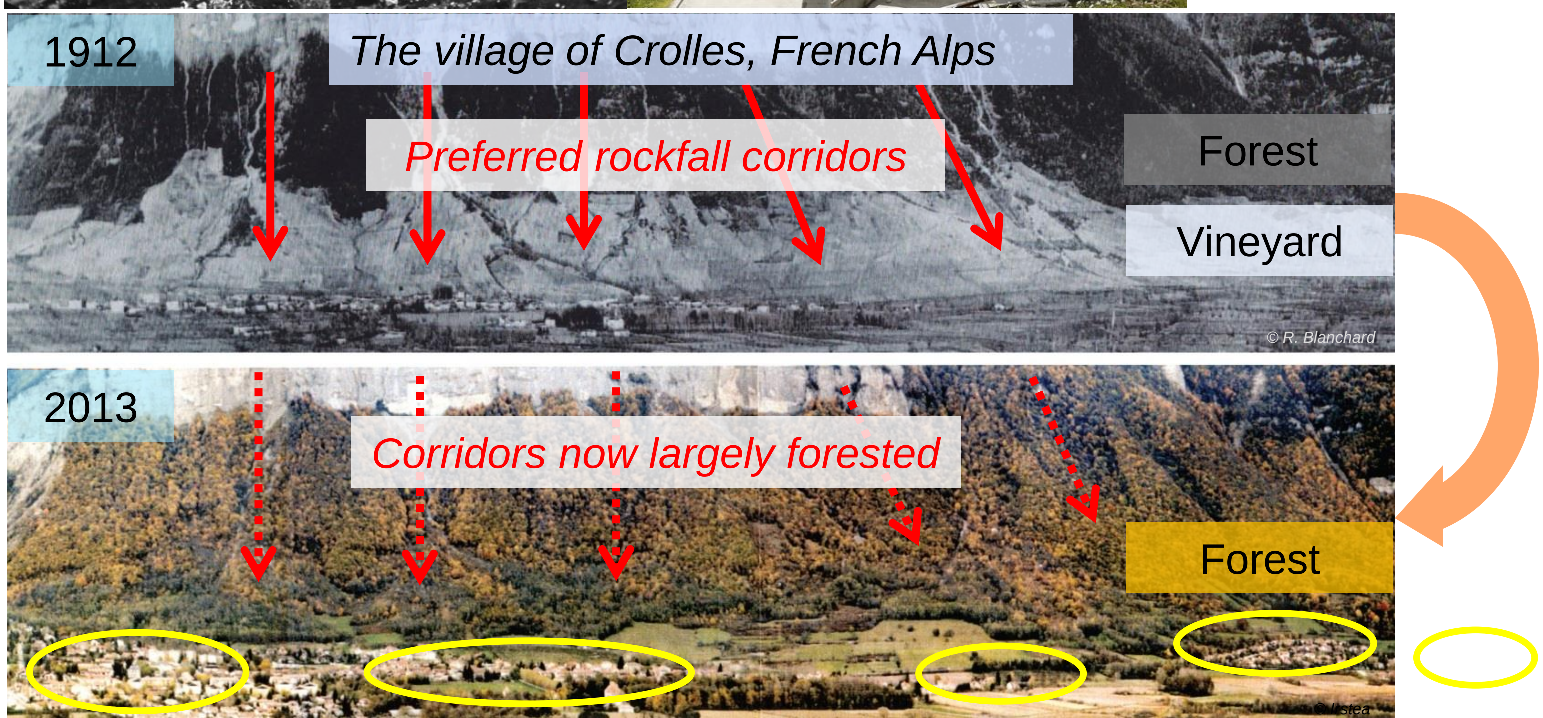


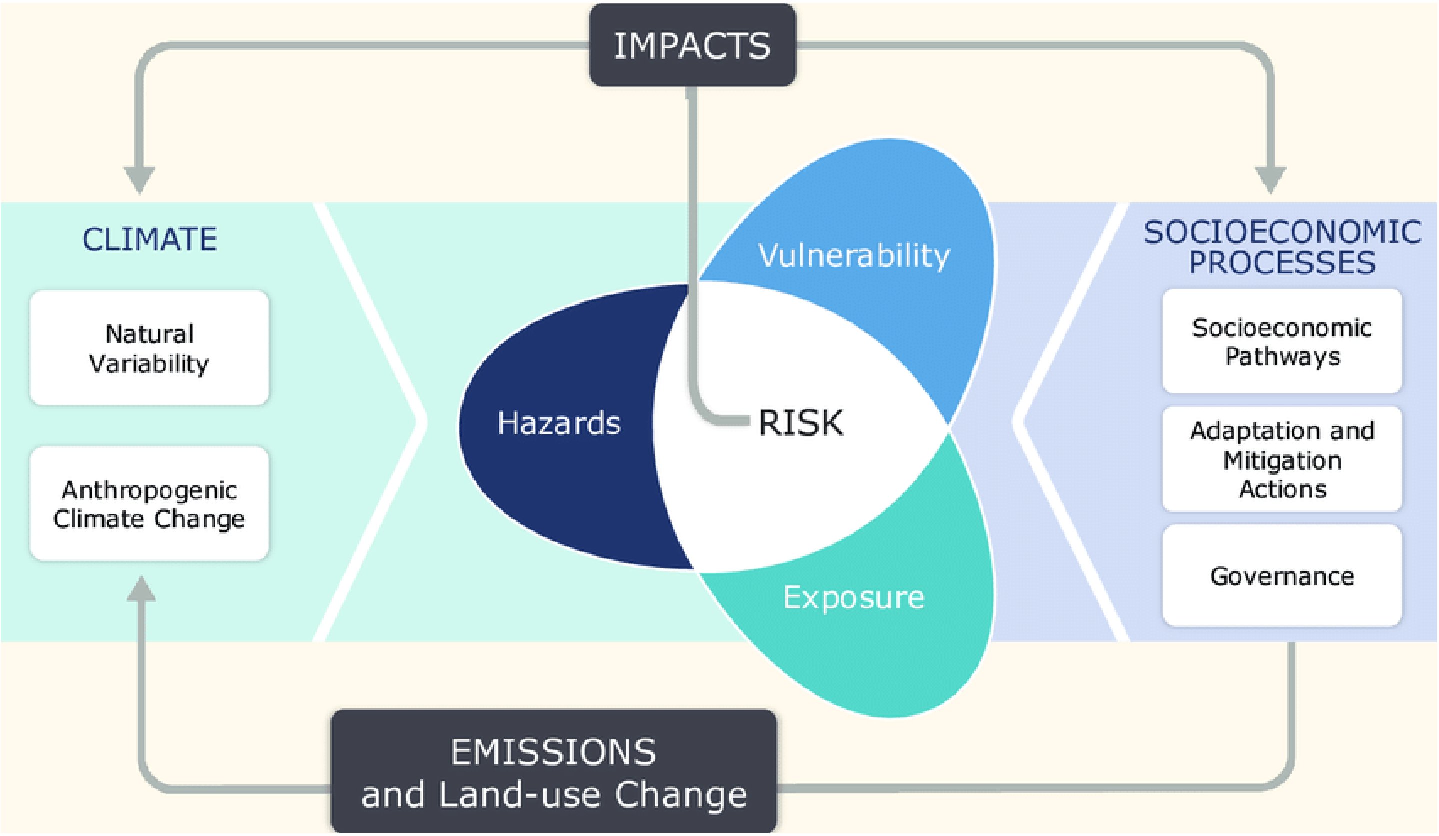
Rockfall Hazard −

Exposure ++

Risk +

Main recent settlements

Risk conceptualisation (IPCC 2014)



- ***Explicit combination of hazard, exposure and vulnerability.***
- ***Risk assessment***: evaluation of "expected" damage as a function of space, combining the magnitude-frequency relationship of the phenomenon with elements at risk.
- ***Risk mitigation***: taking measures that can reduce the expected damage to a value that is considered acceptable.

Short and long term assessment and mitigation

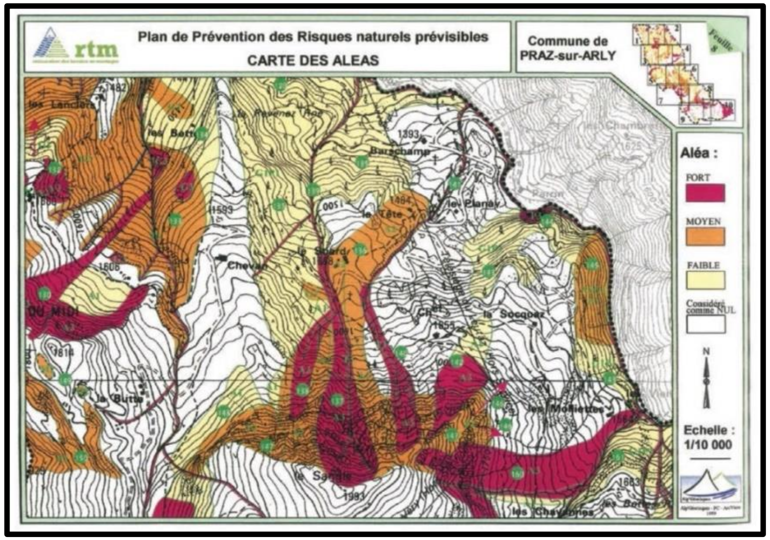
- ***Long term***:
  - Land-use planning (lack of space): where to “draw the line”? Building defense structures?
  - Return levels
  - “Unconditional” modelling

- ***Short term***:
  - When closing a road? A ski slope?
  - When evacuating a settlement?
  - Forecasts conditional to snow and weather (traffic) conditions

Recurrent and emerging hazards / risks

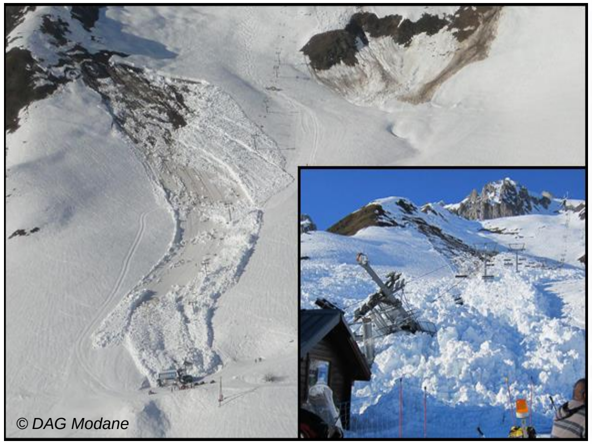
- Recurrent hazards: long term forecasting on the basis of history. Yet, frequency, magnitude, timing, typology, etc. may be affected by environmental changes.
- Emerging hazards: “new” phenomena related to glacier shrinkage, permafrost thawing, mutation of ecosystems, etc.
- “Grey” boundary between these classes.

Emerging hazard: hanging glacier at Aiguille du Midi



Legal hazard (avalanches, landslides, rockfall, torrential flood) map of Praz sur Arly (Haute Savoie, France) reprinted from MEDDE (2015). Colored surfaces correspond to strong, medium and low hazard levels according mostly to historical information for recurrent hazards.

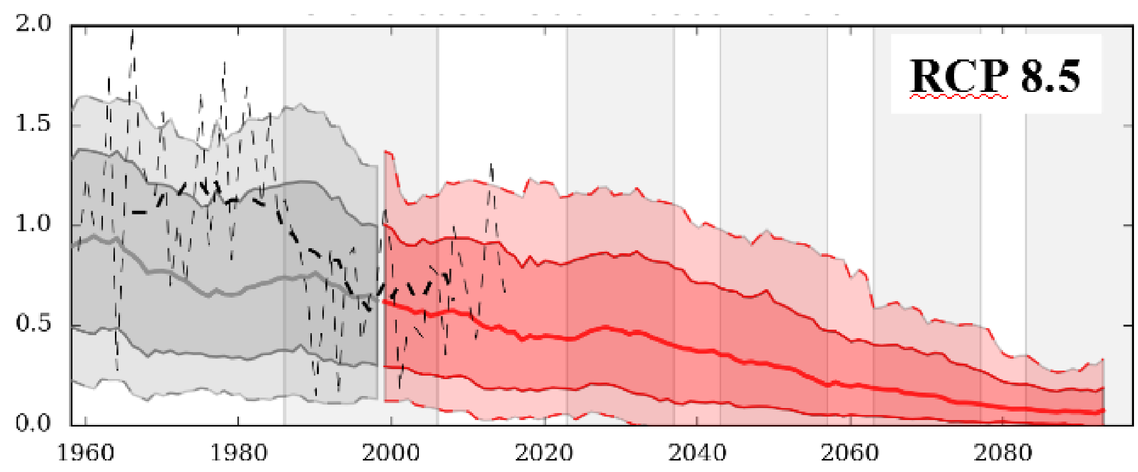
© Data-avalanche.org



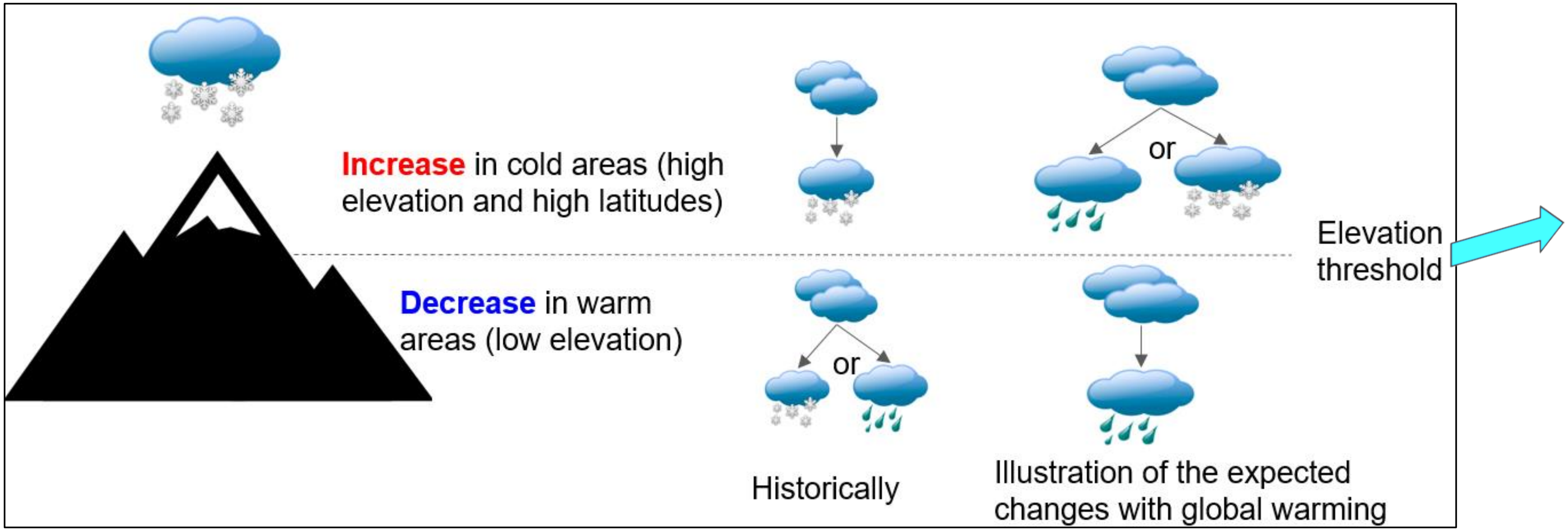
Changing hazards: wet snow avalanches

Physical processes: what's going on ?

- Temperature and precipitation tend both to increase, temperature much more strongly.
- "Everything" starts with snowfall.
- Critical role of the rain/snow partition, with an elevation threshold raising with warming.

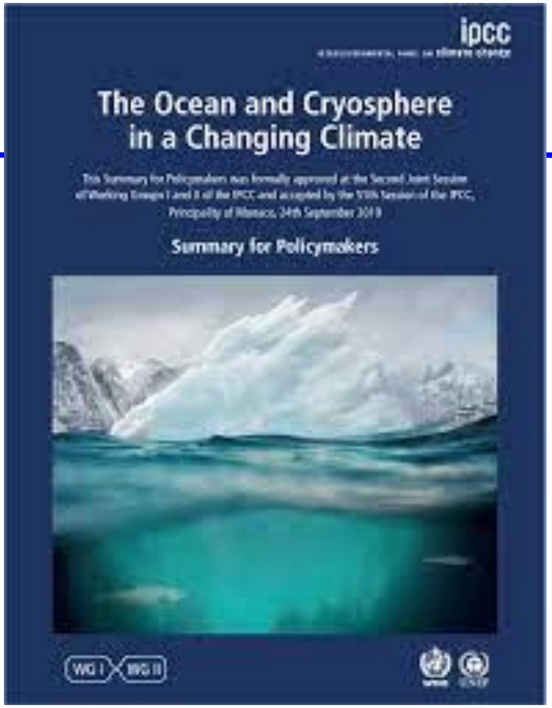


Mean winter snow depth at Col de Porte, 1800 m a.s.l. (Verfaillie et al., 2018)

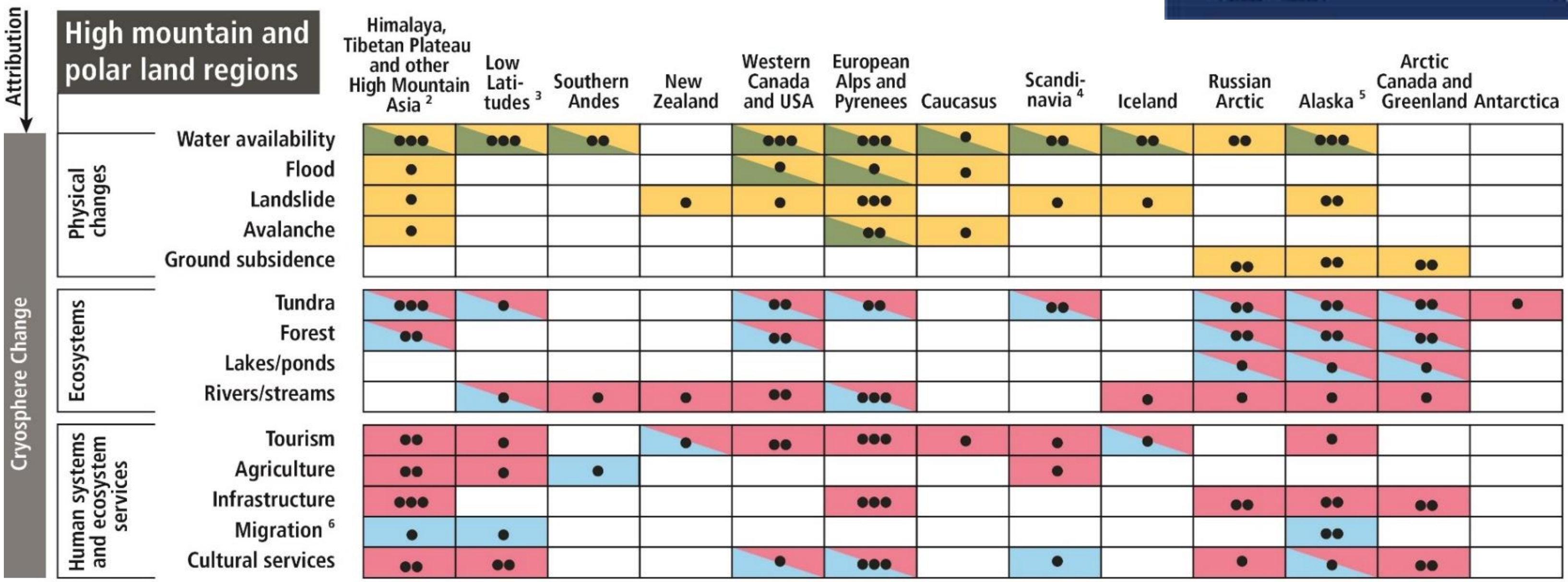


Changes in snowfall with increasing temperature and precipitation (adapted from Le Roux 2022)

State of the art: IPCC SROCC



- Specific mountain chapter.
- Changes in climate and snow variables.
- Dashboard regarding mountain hazards and related risks (incl. vulnerability and exposition).

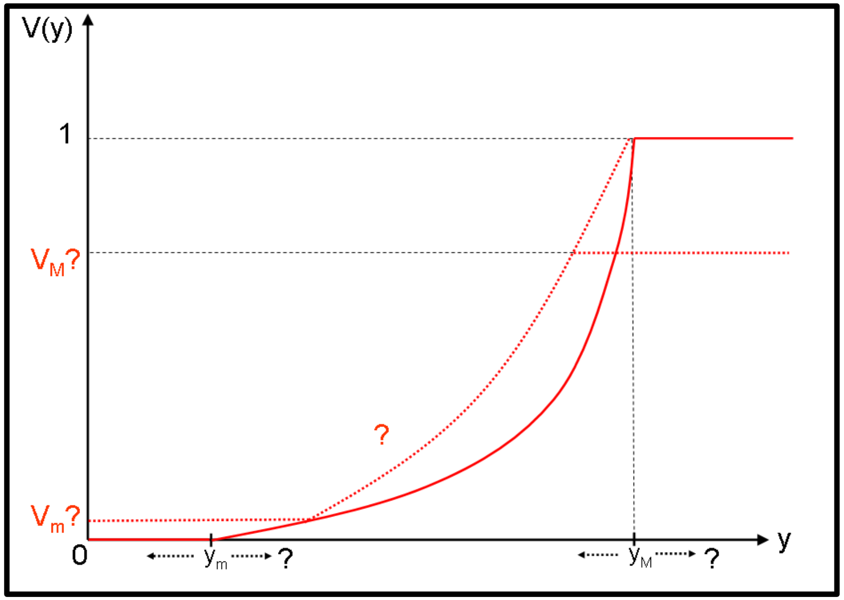


[2] including Hindu Kush, Karakoram, Hengduan Shan, and Tien Shan; [3] tropical Andes, Mexico, eastern Africa, and Indonesia; [4] includes Finland, Norway, and Sweden; [5] includes adjacent areas in Yukon Territory and British Columbia, Canada; [6] Migration refers to an increase or decrease in net migration, not to beneficial/adverse value.

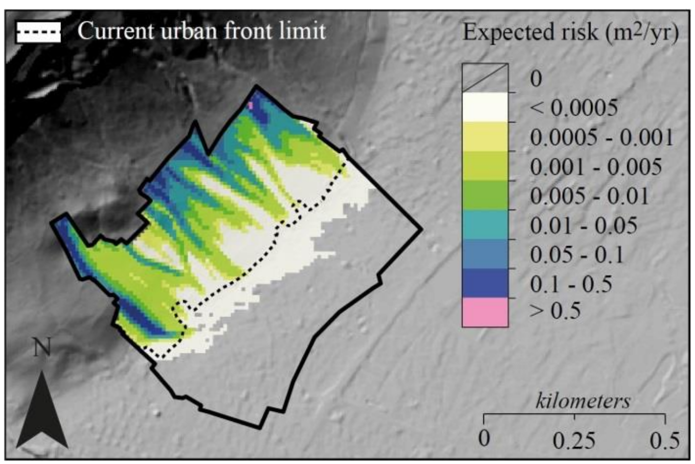
Changes in Mountain cryosphere and related hazards. IPCC SROCC 2019, summary for Policy Makers.

Guidelines (1): risk modelling

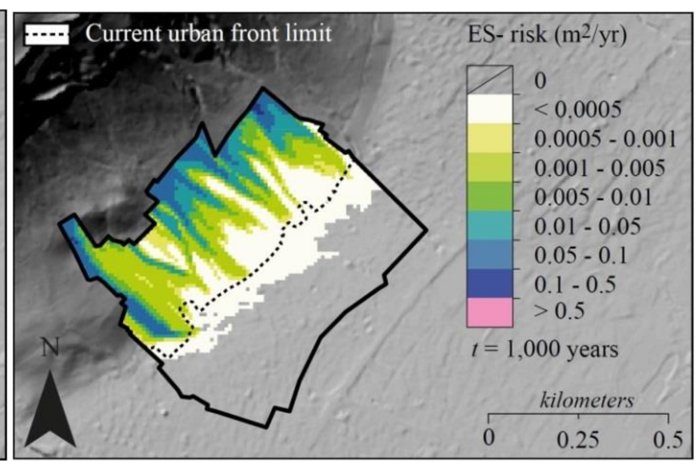
- Modelling hazards within a probabilistic framework and consequences for elements at risks.
- Relies on vulnerability relations: deterministic relation between loss (or destruction probability) and hazard level.
- Risk definition generally retained: ***mean expected loss.***
- Alternative quantile-based risk measures emerging.



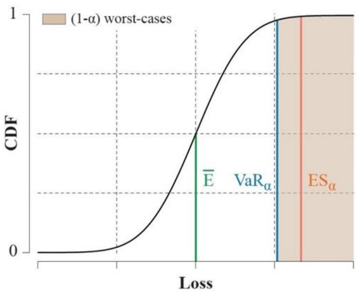
Generic form of a vulnerability relation (Eckert et al., 2012)



Rockfall risk as mean expected loss



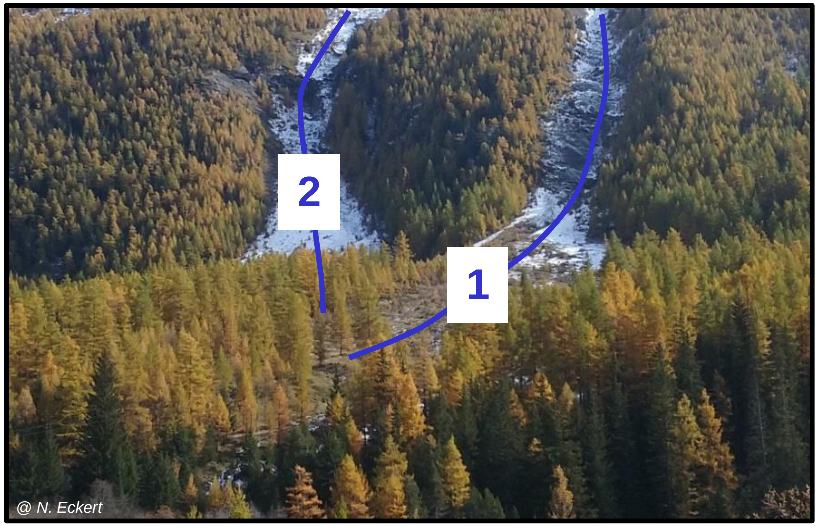
Rockfall risk as expected shortfall over 1,000 years



Rockfall risk as function of space in Crolles Municipality, Farvacque et al. (2021)

Guidelines (2): modelling spatio-temporal dependences

- Going beyond local modelling under the stationarity assumption:
  - Taking into account climate, environmental and/or social changes
  - Sparse data: information transfer to undocumented sites

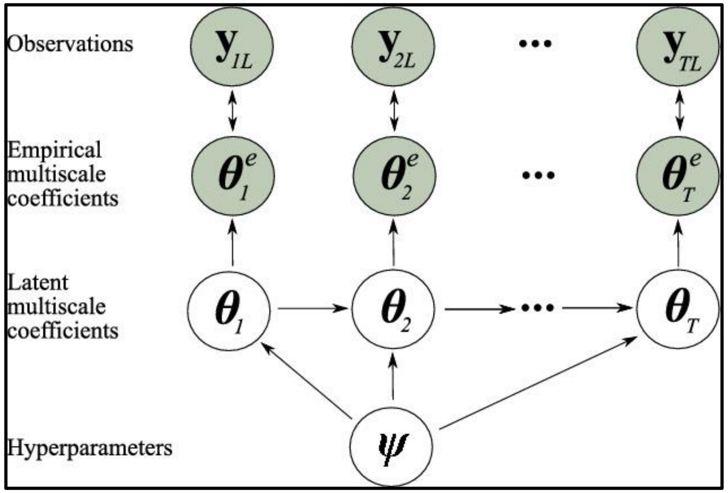


Path 1 is well documented: using data for hazard assessment on path 2?

Runout zone is in rapid afforestation: unsteady return levels?

- Hierarchical Bayesian space time modelling as a suitable framework.

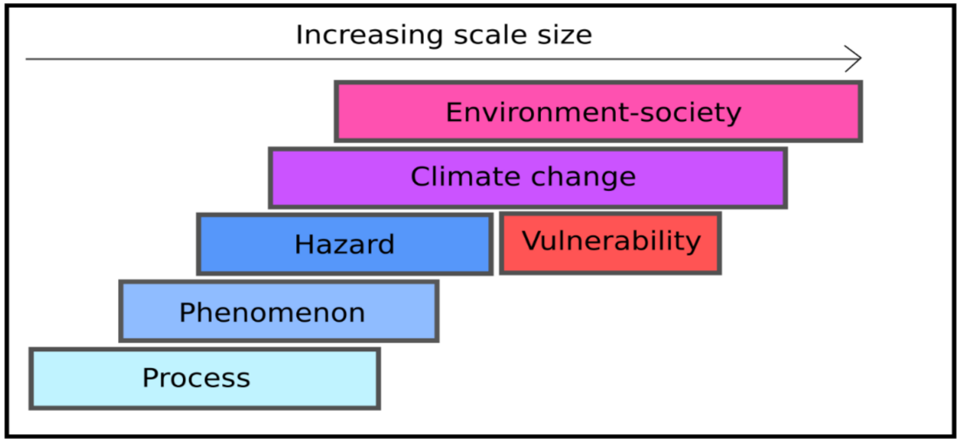
- Time and space explicit or implicit ("physical" covariates).



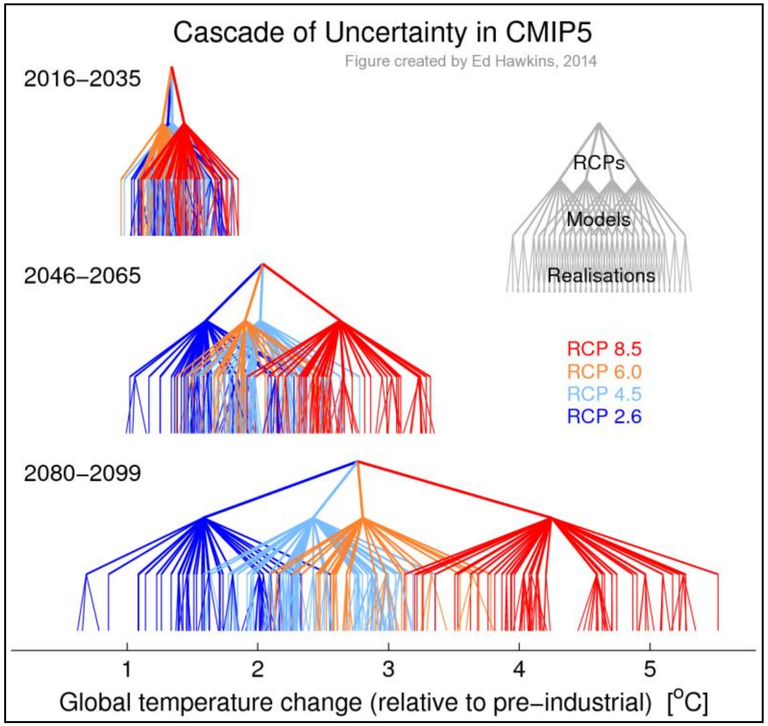
Generic representation of a hierarchical spatio-temporal model (Ferreira, 2020)

Guidelines (3): linking scales

- Hazard / risk concern "intermediate" scales.
- Strong links with smaller / larger scales and objects: necessity of relating small – scale processes to global trends.
- "Top-down" approach of climate simulations ~ hierarchical structure.



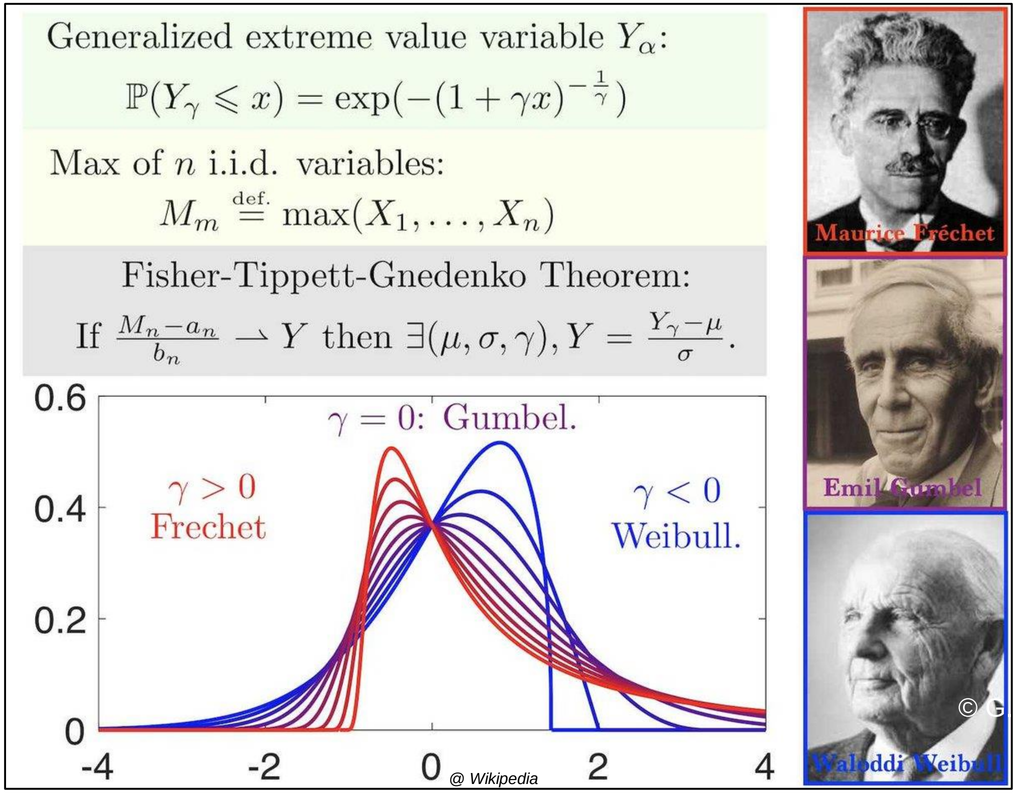
Adapted from Eckert (2017)

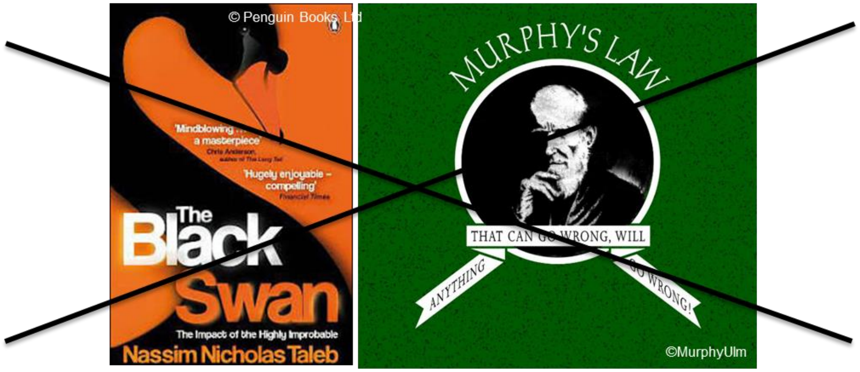


Ensemble simulations of future climate (Hawkins, 2014)

Guidelines (4): dealing with extreme events

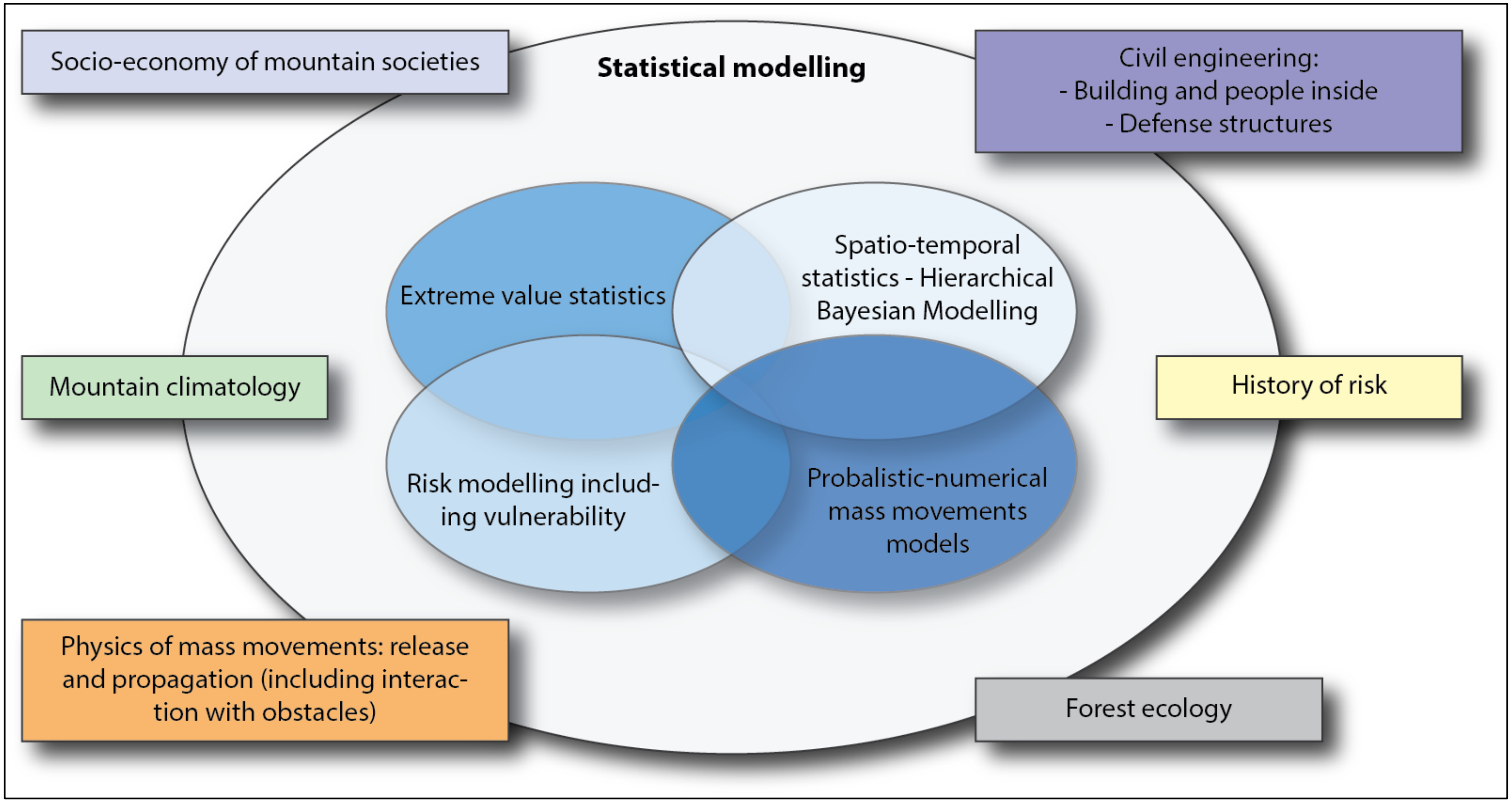
- Short series to predict rare events.
- Robust methods to extrapolate beyond observational records required.
- Extreme value theory and related statistical models : GEV, GPD, Max Stable processes, etc. as a readily usable, operational framework.





Guidelines (5): combining disciplines

- Accounting for physics, but not only!
- Always useful, sometimes mandatory to be accepted.
- Statistical modelling as a suitable framework to integrate “everything”.



Assessing and mitigating mountain risks: combining knowledge and disciplines with statistical modelling, adapted from Eckert (2017)

Context, concepts and guidelines

Glaciers and glacier risks

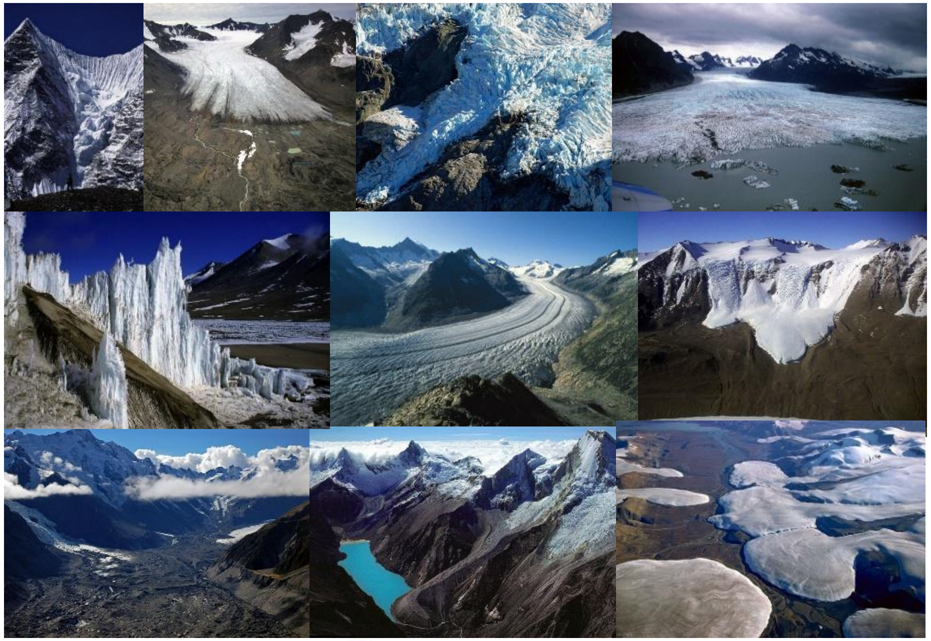
Snow extremes and related risks

Snow avalanche risk

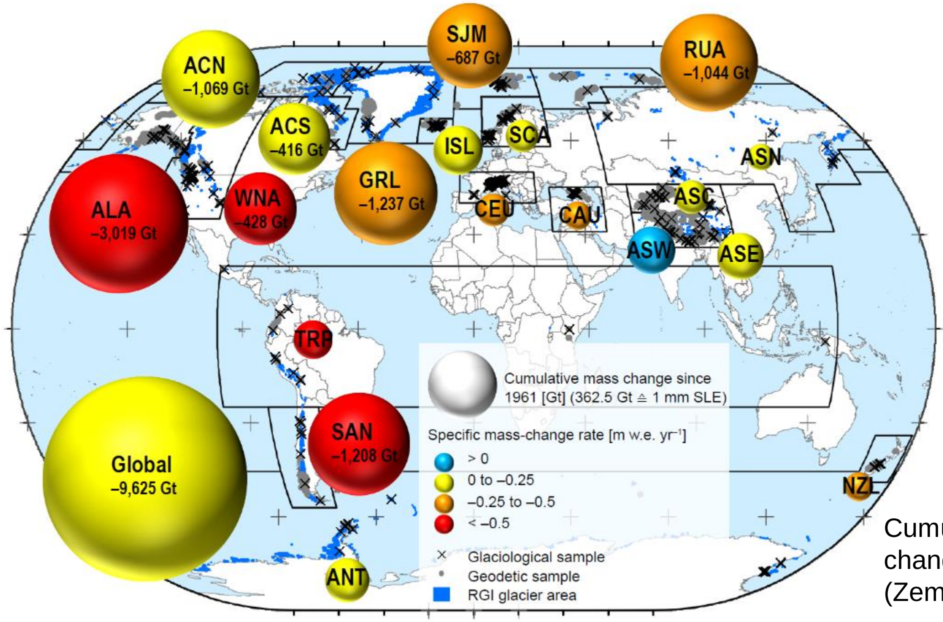
Take home message

Glacier changes: the “easy” case

- Excellent databases (World Glacier Monitoring Service) summing-up long-term field measurements, remote sensing data, etc.
- “Smooth” evolution with temperature and precipitation.
- Continuous improvements of local to worldwide assessments, with “tricks” to link scales / data sets.
- Sea-level rise equivalent.
- Attribution of glacier melt to anthropogenic warming (Marzeion et a., 2014).



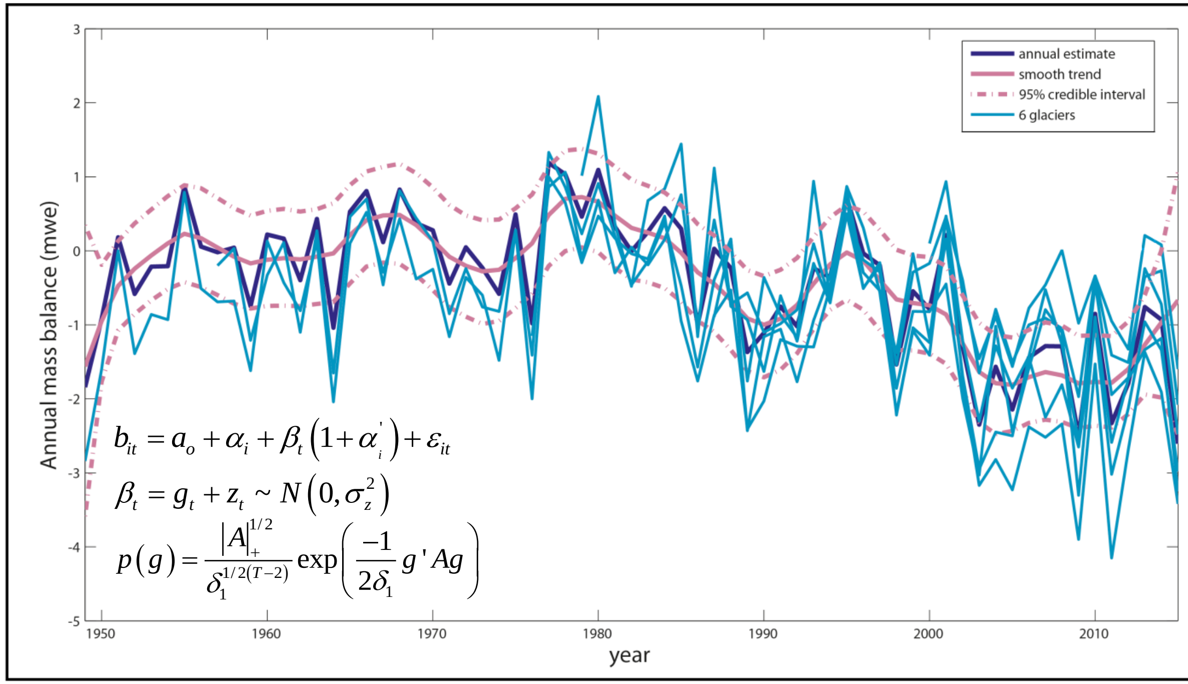
215,000 glaciers (158,000 km³) distinct from the Greenland & Antarctic Ice Sheets, Fratinotti et al. (2019)



Cumulative glacier mass changes 1961-2016 (Zemp et al., 2019)

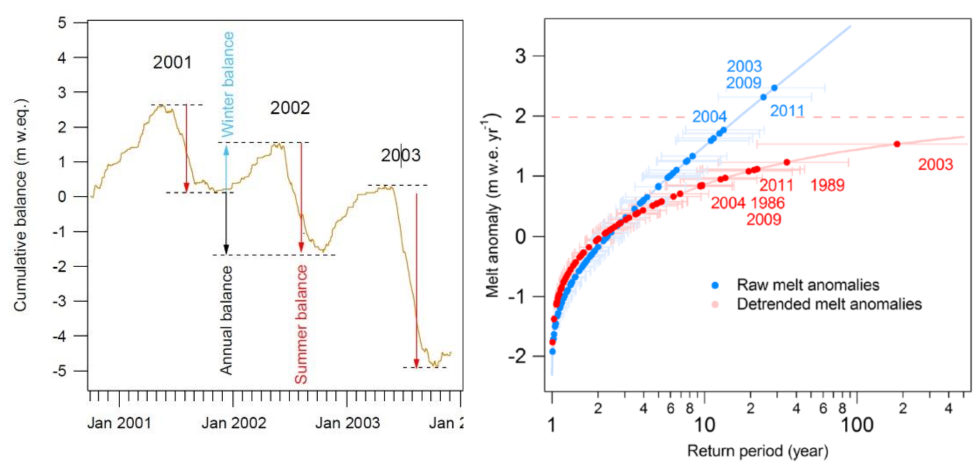
Glacier changes: challenges remaining

- Better combine data of various nature / spatio-temporal resolution to improve assessment at centennial time scales.



Regional trend in glacier changes in the French Alps from available series of uneven length (Eckert et al., 2016)

- EVT-framework: annual and winter balance as maxima, relation to extreme precipitation and heat waves.



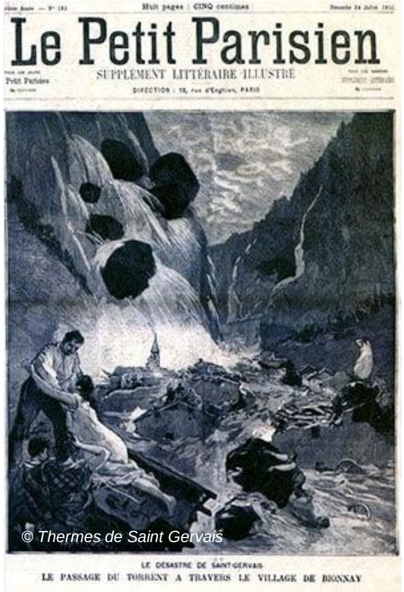
Glacier mass balance within EVT framework, application to melt extremes at Sarennes glacier (Thibert et al., 2018)

Glacier risks : the “black hole”

- Extreme multiplicity of processes / risks: icefall, GLOFs, sediment supply, debris flows, etc.
- Extreme non-stationarity.
- Very rare but catastrophic, far-reaching consequences.
- Current approaches: susceptibility mapping, simulations (potential extensions), monitoring and evacuations when critical state is reached.
- “PAPROG” program in France, manpower required!

Chamoli (India) burst flood, 2021 : 50-200 casualties

GLOF in Saint Gervais, 1892, (175 casualties)


Huit pages | CINQ centimes

Le Petit Parisien

SUPPLÉMENT LITTÉRAIRE ILLUSTRÉ

DIRECTION : 18, rue d'Enghien, PARIS

LE DÉSASTRE DE SAINT-GERVAIS

LE PASSAGE DU TORRENT A TRAVERS LE VILLAGE DE BIONNAY

Potential glacier collapse (Aosta Valley, 2020) and evacuated area

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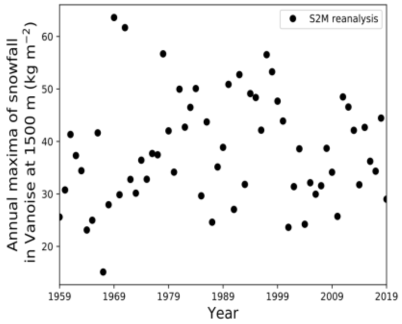
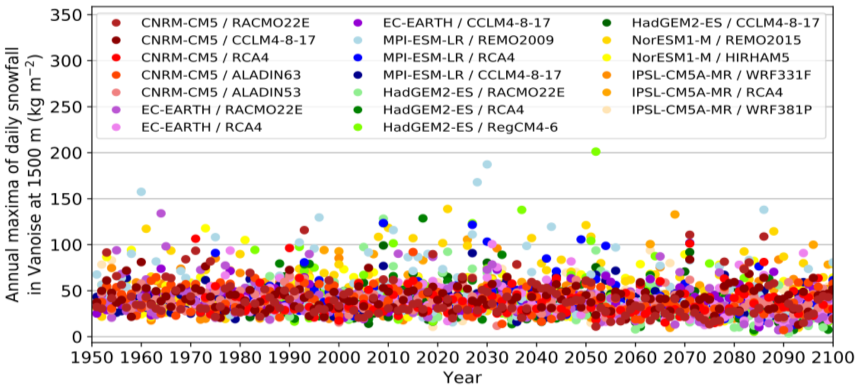
Take home message

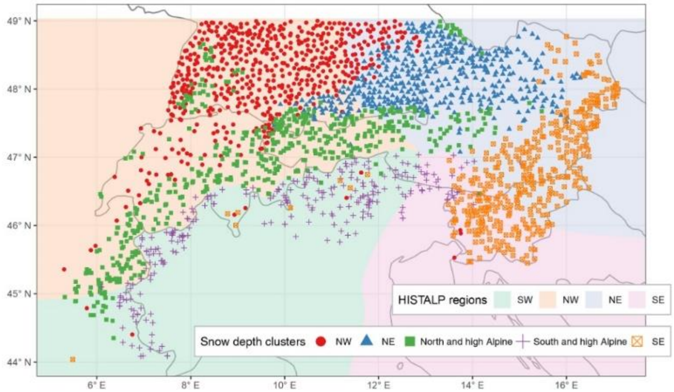
Snow extremes: context

- “Long” instrumental data available for snowfall, a bit less for snow depth and further snow cover characteristics.
- Station data, reanalyses and outputs of climate modelling chains available at daily time scale: “classical” framework in statistical climatology, standard tools from EVT readily usable.
- Trend analyses at country scale, one study at the European scale for snow depths, some country scale assessment of changes in Extremes (Switzerland: Blanchet and Marty, 2012), France, etc.
- Theoretical evolution of extreme snowfall with increasing temperature according to physical rules (O’Gorman, 2014).



Annual maxima of snowfall for the Vanoise massif at 1500 m: S2M reanalysis (1959-2019, Lafaysse et al., 2019) and 20 Adamont climate projections (1950-2100) for scenario RCP8.5 (Verfaillie et al., 2018).





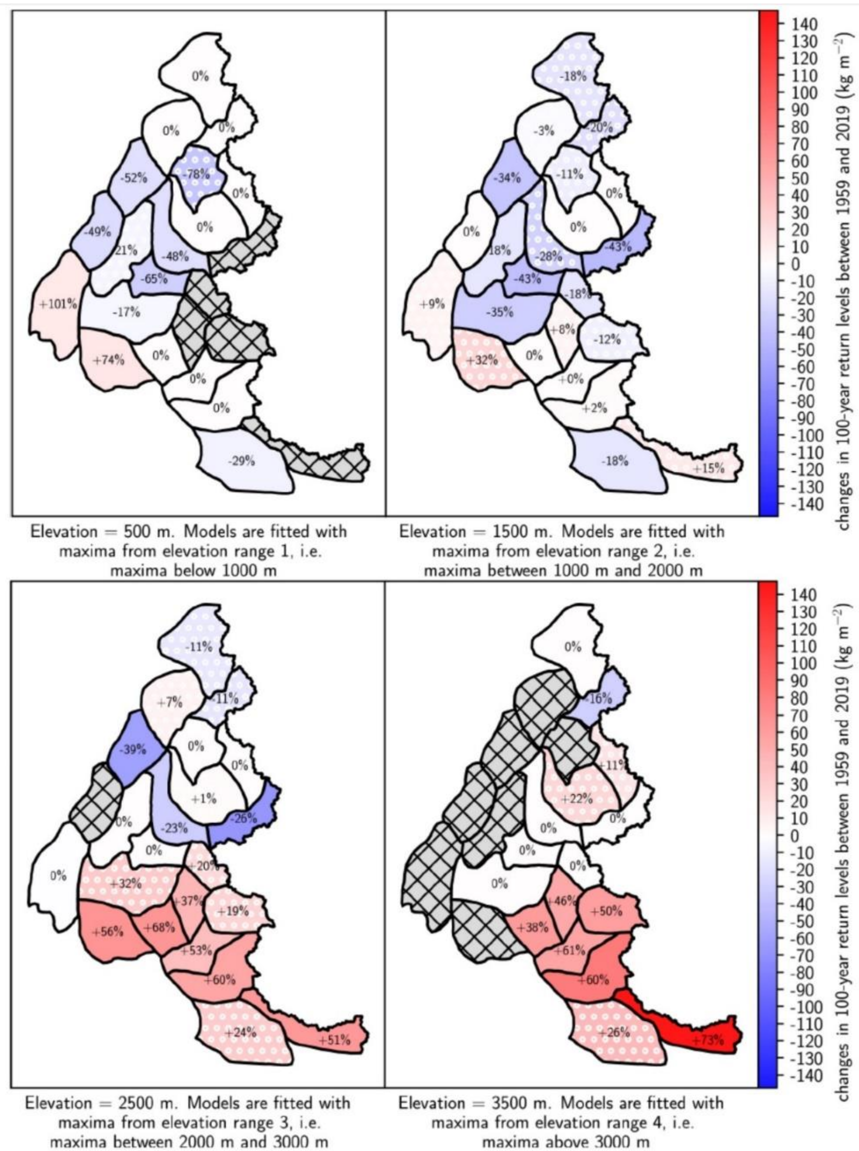
European-scale assessment of 1971-2019 snow depth trends: clustering and trend analysis (Matiu et al., 2019).

Past changes in extreme snowfall

- Non-stationary GEV models as function of massif and elevation

$$SF(i,t,z) \sim GEV\left(\mu(i,t,z),\sigma(i,t,z),\xi(i,t,z)\right)$$

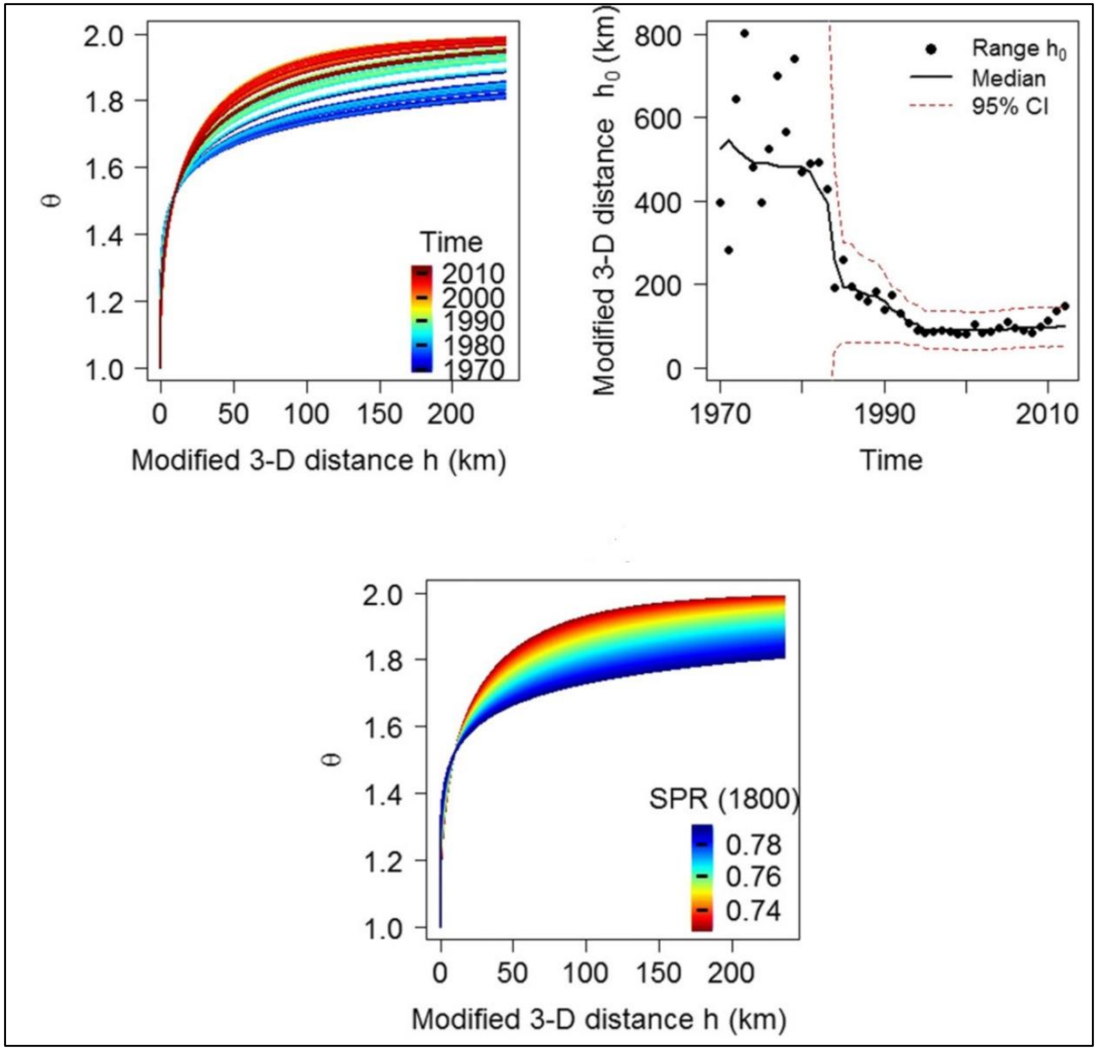
- Model selection procedure for best parametrisation.
- Evolutions results from the competition between increasing temperature and increasing precipitation.
- PhD of Erwan Le Roux: will be defended tomorrow, 2PM. Join on Zoom!



Changes in 100-year return levels of daily snowfall between 1959 and 2019 for each range of elevations, from Le Roux et al. (2021)

Past changes in dependence structure with warming

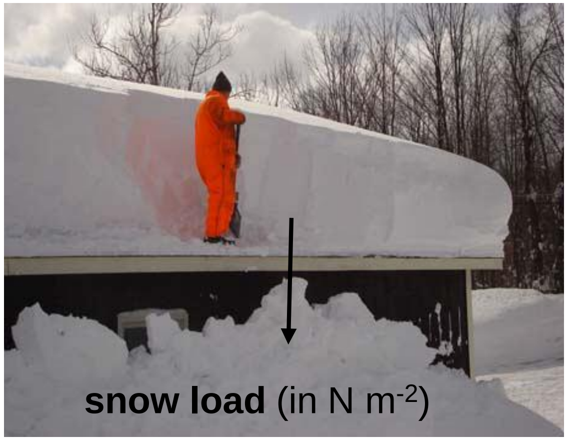
- Extreme snowfall / snow depths as continuous function of "space".
- Extremal coefficient (Schlather & Tawn, 2003, Naveau et al., 2009) as function of time, or of some temperature/precipitation covariates / implicit time dependency (Nicolet et al., 2016; 2018).
- Strong decrease in dependence range, independent from the trend captured by the margins.
- To be done: combining non stationarity in margins and dependence structure.

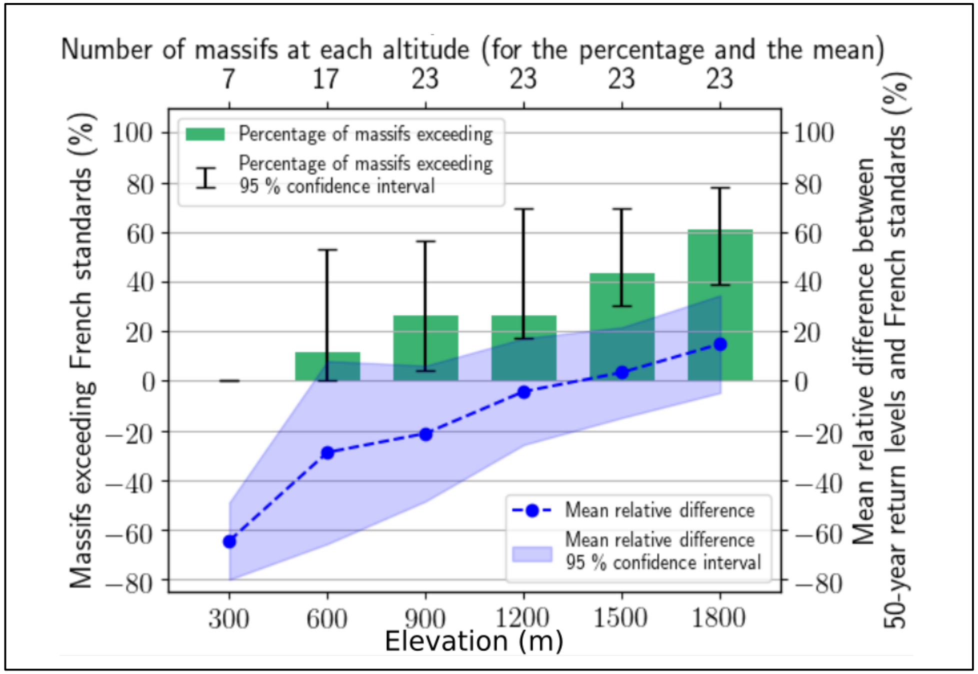


Spatio-temporal modelling of extreme snow depths in the French Alps (Nicolet et al; 2018). Evolution of the modelled extremal function (full max-stable Brown Resnick process fitting) according to time, distance and Snow Precipitation Ratio at 1800 m a.s.l., respectively.

Risks related to snow extremes

- Short-term risk: “meteorological” problem.
- Long term risk: mainly roof collapse : evaluation of return levels for snow loads (depth times gravity) as straightforward risk measure.
- Misc: systematic mapping of the risk of collapse for theoretical or real buildings.





1959-2019 changes in 50-year return period snowload for the massifs of the French Alps and comparison to current building standards (Le Roux et al., 2021).

Roof collapse due to snowload, Gyeongju (South Korea) (2014), 10 casualties and more than 100 injured.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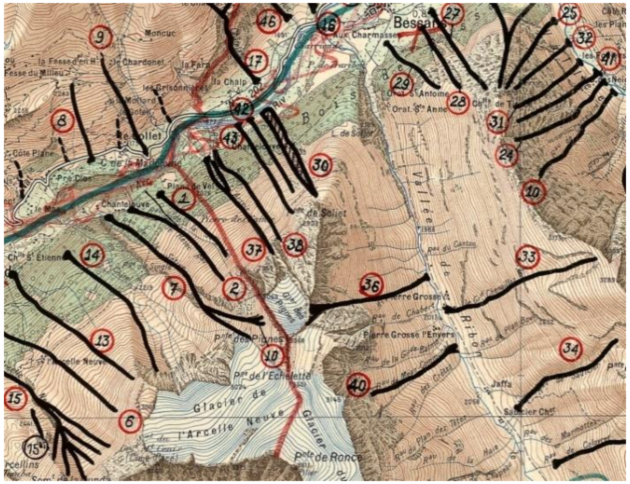
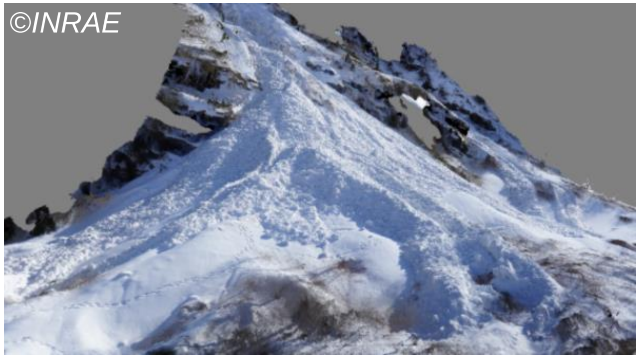
Snow avalanches: context

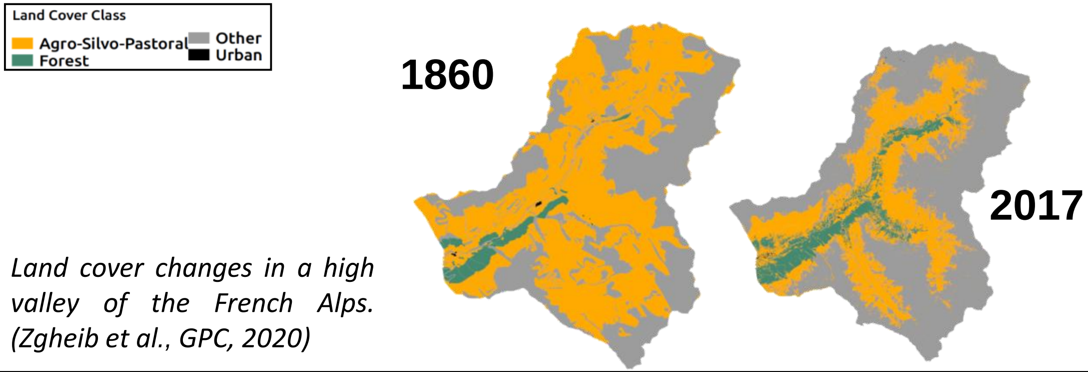
- Data difficult/dangerous to acquire : overall, sparse/lacunar time series.
- No large-scale assessment of changes in hazard and related risks currently available, a few results for massifs in Europe, North America, India and Japan.
- In France “excellent” data:
  - Avalanche database “*EPA*” (~4000 selected paths);
  - Top-seed measurements (LIDAR, remote sensing);
  - Archival and paleo-environmental data.
- “Full set” of environmental data: past and future snow and weather conditions, past land cover and population changes, etc.



Historical avalanche map (Mougin, 1922) on which avalanche paths were drawn manually



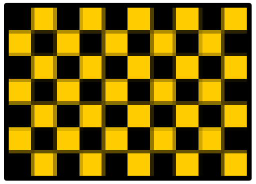
3D avalanche deposits measurements in the same area



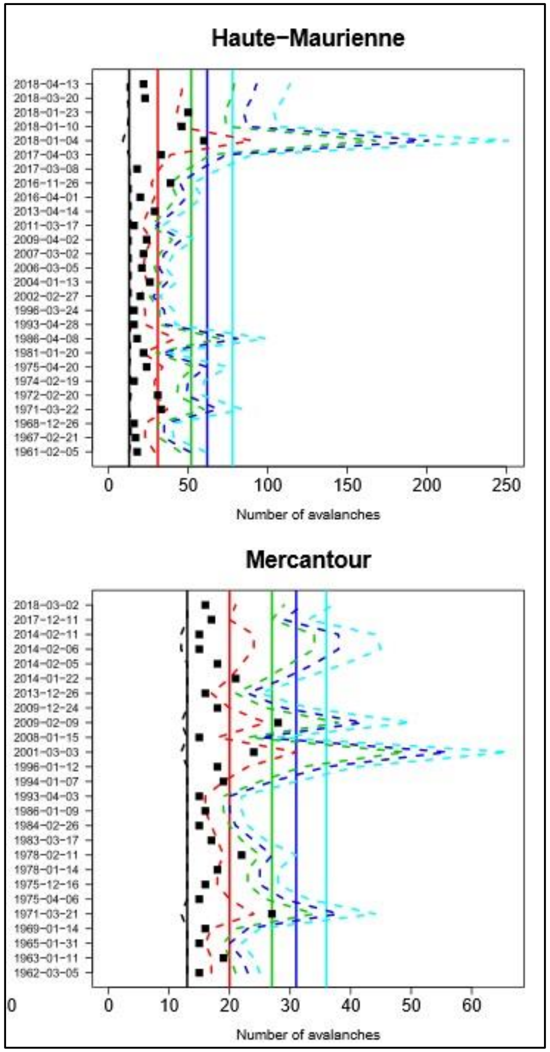
Land cover changes in a high valley of the French Alps. (Zgheib et al., GPC, 2020)

Short-term forecasting

- “Classical” forecasting problem conditional to snow conditions.
- Use of basic to deep learning techniques.
- Forecast as a deterministic classification problem, or probabilistic forecasts of avalanche numbers / hazard level.
- No “full” risk assessment but risk for skiers by taking into account additional loading (accidental trigger).
- No consideration of underlying climate change context (observations taken as exchangeable, except within the same winter).



Avalanche operational forecasting: real time snow and weather data assimilation and modelling and expert evaluation of a 5 classes “risk” level.



Probabilistic forecast of avalanche numbers in two French massifs using discrete GPD models (Evin et al., 2021).

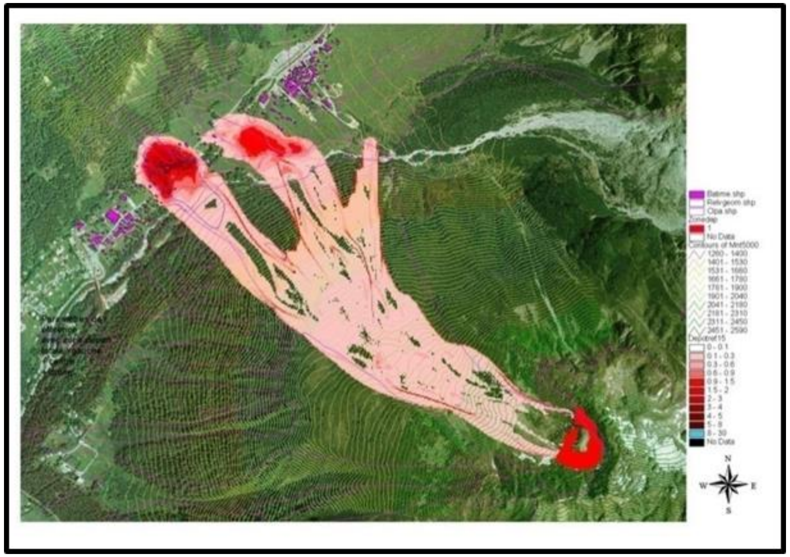
$$NA(i,t) \sim dGPD(\sigma x(i,t), \xi)$$

$x(i,t)$: climate drivers

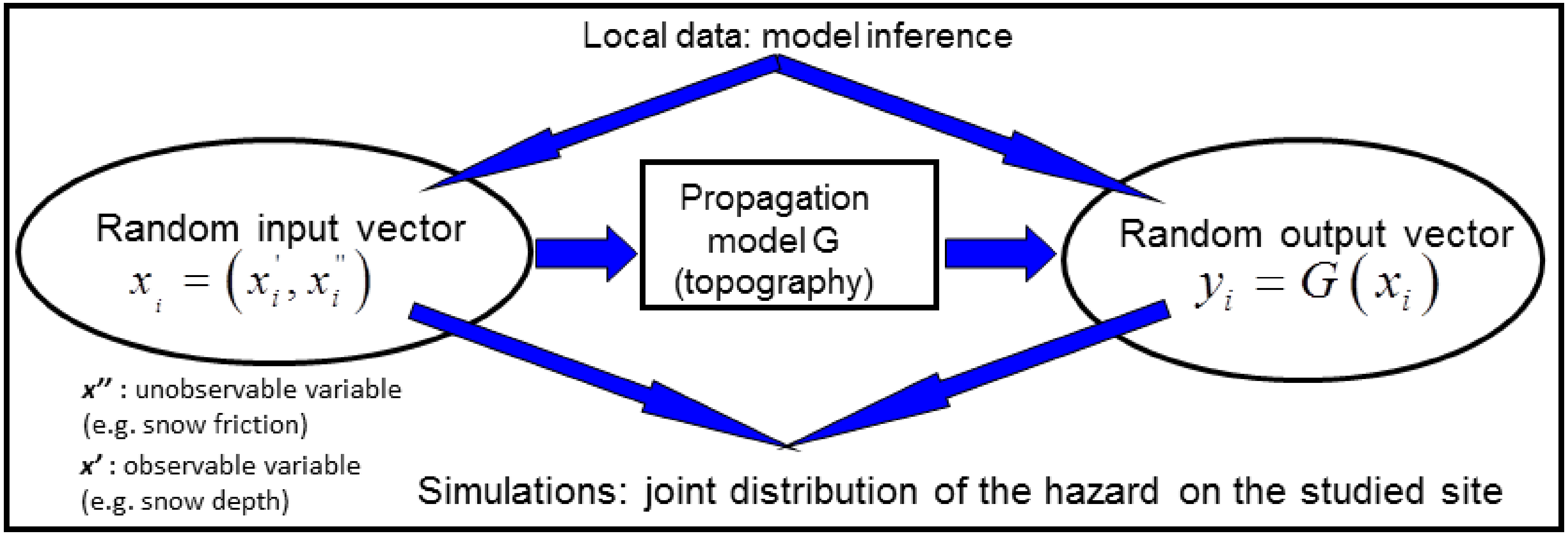
Numerical-probabilistic long term forecasting (1)

- Evaluation of unconditional return levels usable for hazard and risk assessment in runout zones.

- Physically based model with probabilistic framework: not explicit for “outputs”, but multivariate and using real topography and “robust” physics.



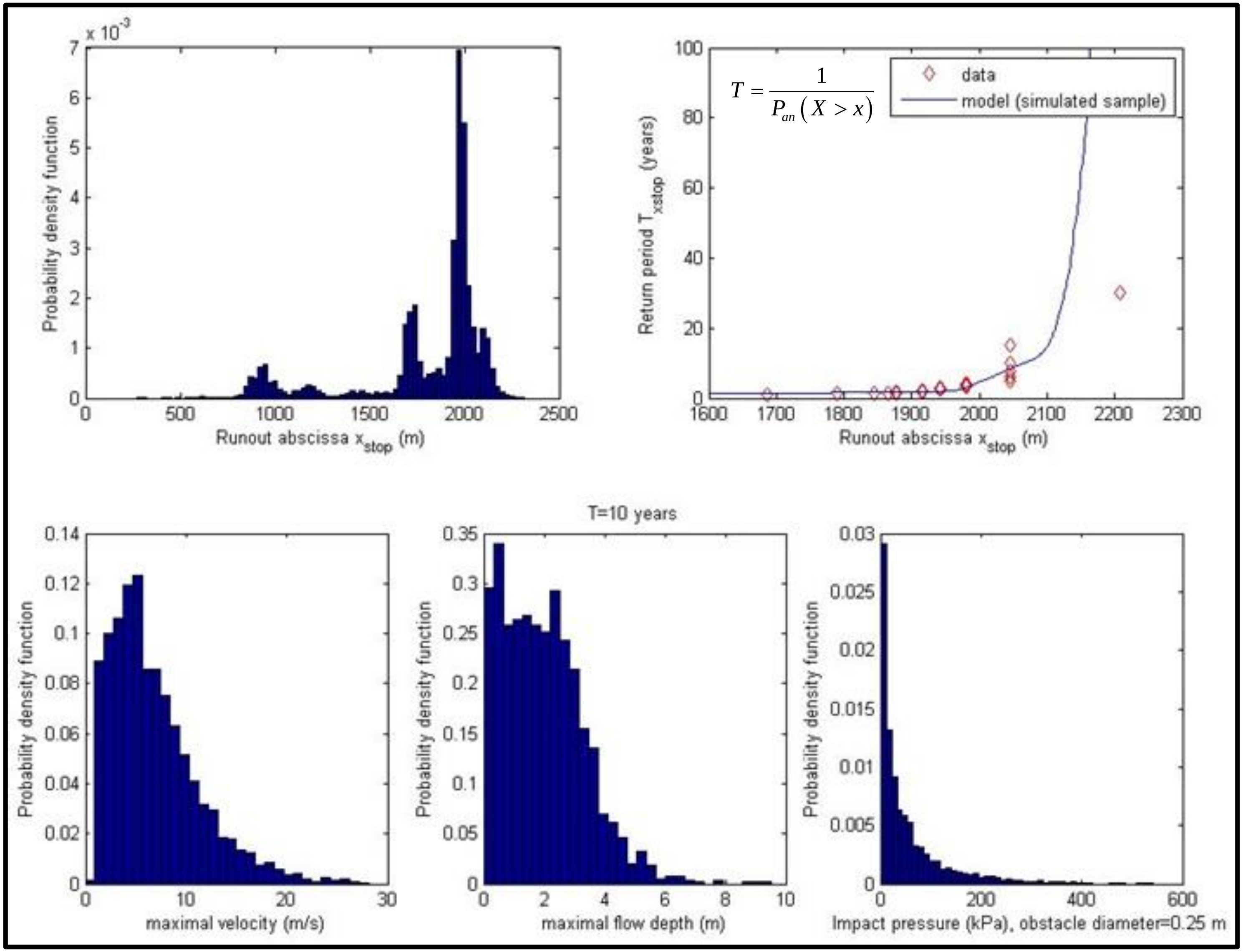
Avalanche simulation for hazard mapping, © M. Naaim, INRAE



Principle of a numerical-probabilistic approach associated with Bayesian inference (Eckert et al., 2007)

Numerical-probabilistic long term forecasting (2)

- *Pseudo POT model relying on a* depth-averaged flow code.
- *Bayesian inference* using *MCMC techniques.*
- Different compromises between computation times and realism of the physical description of the flow.

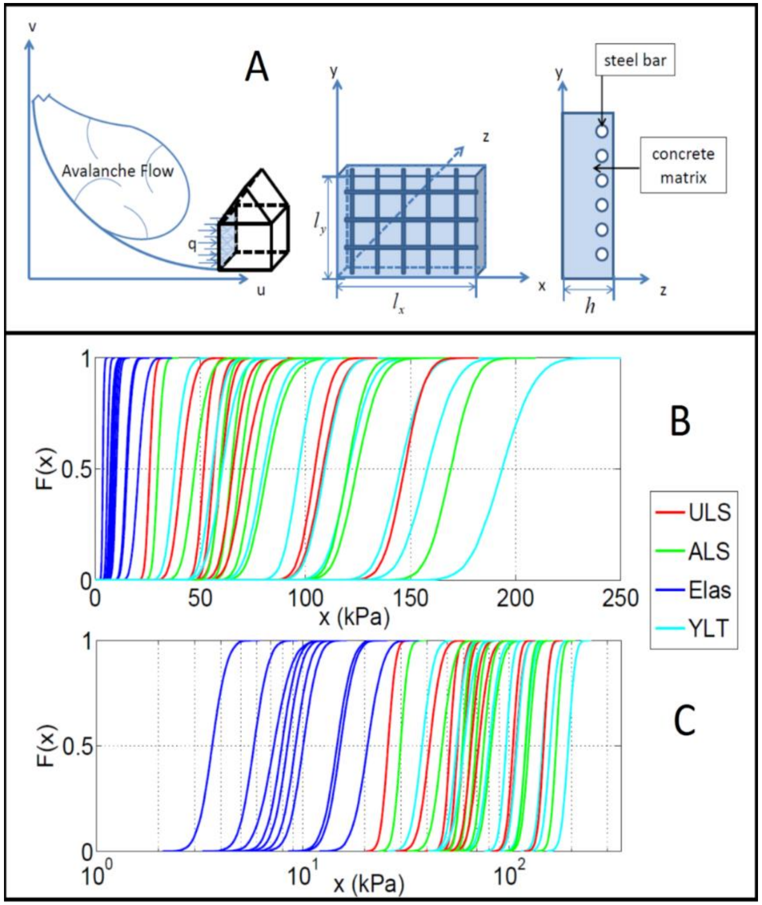


The statistical-dynamical model Eckert et al. (2010) provides the one-to-one relation between runout distance and return period, and, for each runout distance, the joint distribution of all other variables. Impact pressure is computed following Naaim et al. (2008), taking the rheology of snow into account.

Risk for buildings and people inside

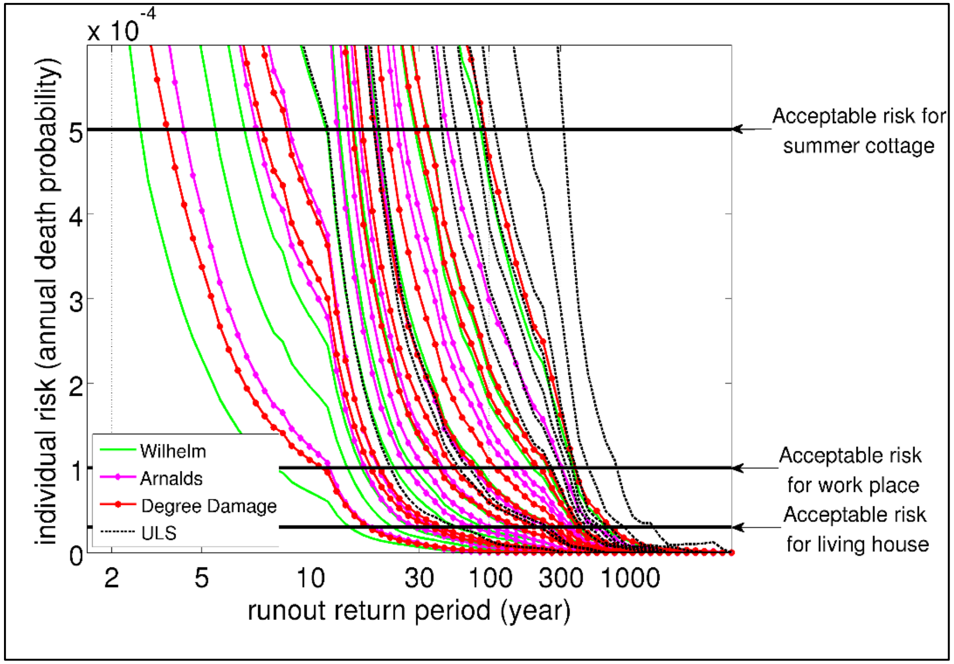
$$R_z \propto E_y\left[V(z,y)\right] = \int p(y)V(z,y)dy$$

- V(z,y): deterministic link between hazard magnitude and damage level for the element at risk z;
- p(y): (stochastic model: describes the variability on the studied site.



Evaluation of fragility curves for various types of reinforced concrete (RC) buildings (Favier et al., 2014a).

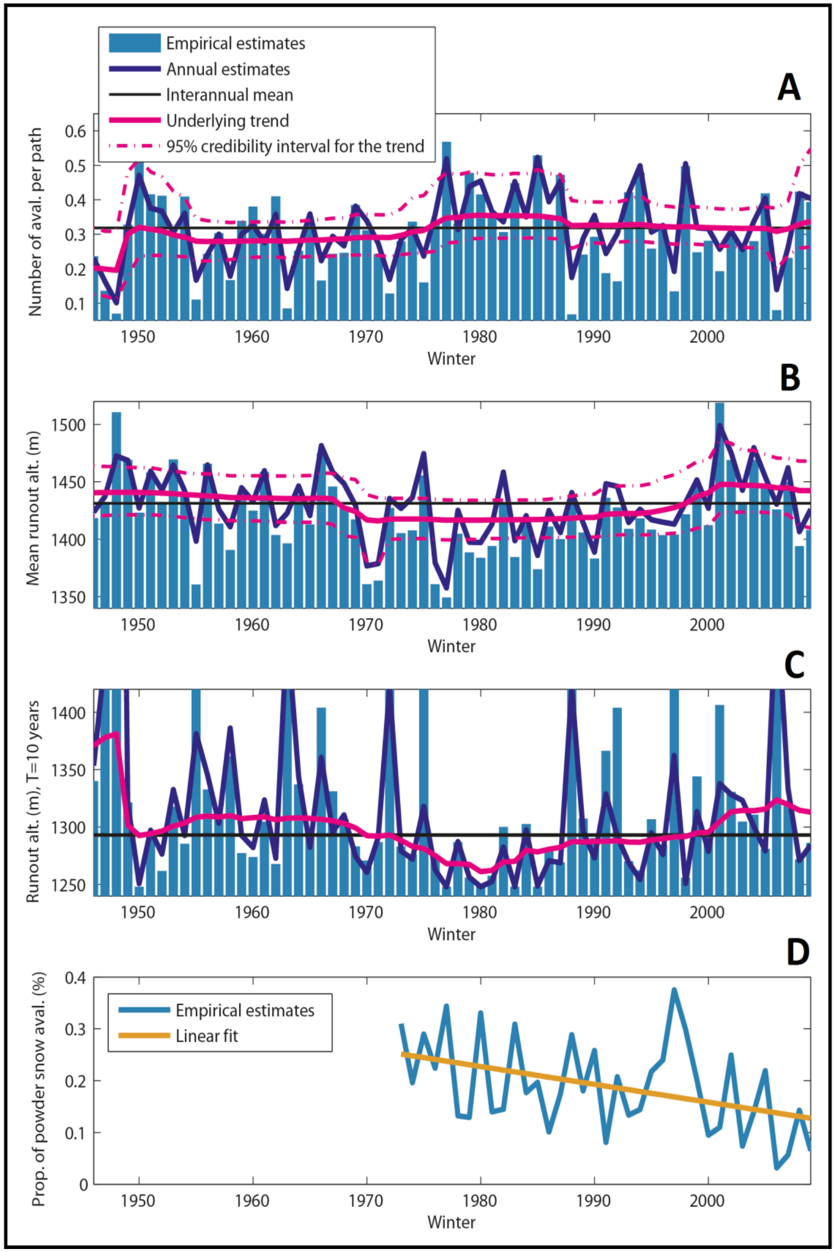
- Evaluation of death rates (individual risk) as function of space in the runout zone.
- Risk less directly linked to hazard intensity as for roof collapse (non linearity).
- Expected damage as standard approach / alternatives in development.



Evaluation of death rates (individual risk) as function of space in the runout zone (Favier et al., 2014b).

Trends inferred from systematic observations in the French Alps over the last decades

- Hierarchical space-time series analysis models.
- Natural avalanche activity series: rather strong evolutions over the 1946-2009 period for numbers, runout altitudes, large avalanches, avalanches with a powder part, wet snow avalanches.
- Empirically, good correlations with winter conditions: pleads for a snow and temperature control of avalanche activity at decadal time scales.

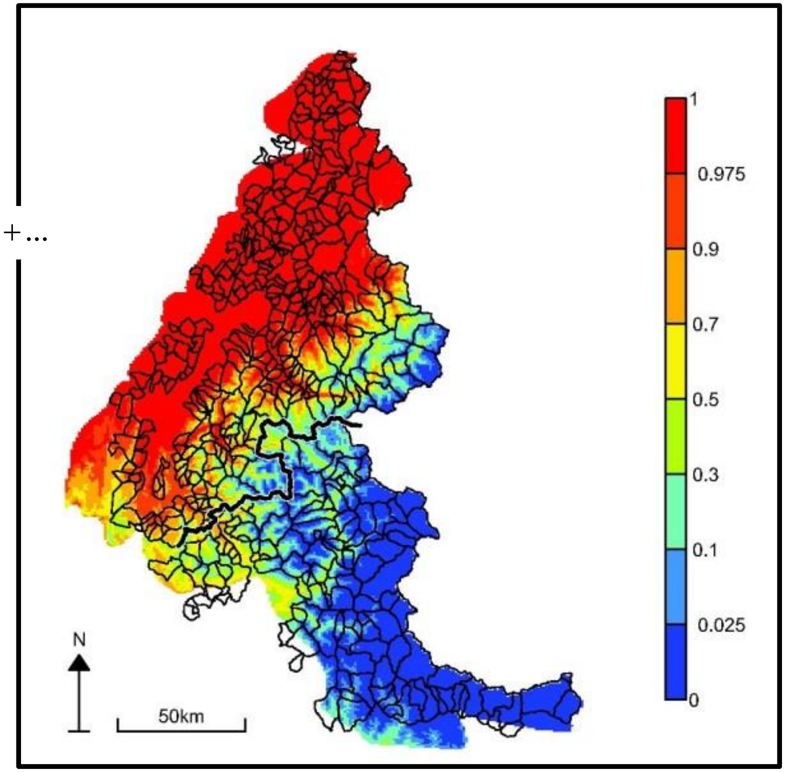


Time trends in different avalanche variables in the French Alps (Eckert et al., 2013). A) Mean number of avalanches per winter and path: annual signal and underlying trend. B) Mean runout altitude. C) Runout altitude corresponding to a return period of 10 years (mean 10 year return level). D) Proportion of powder snow avalanches.

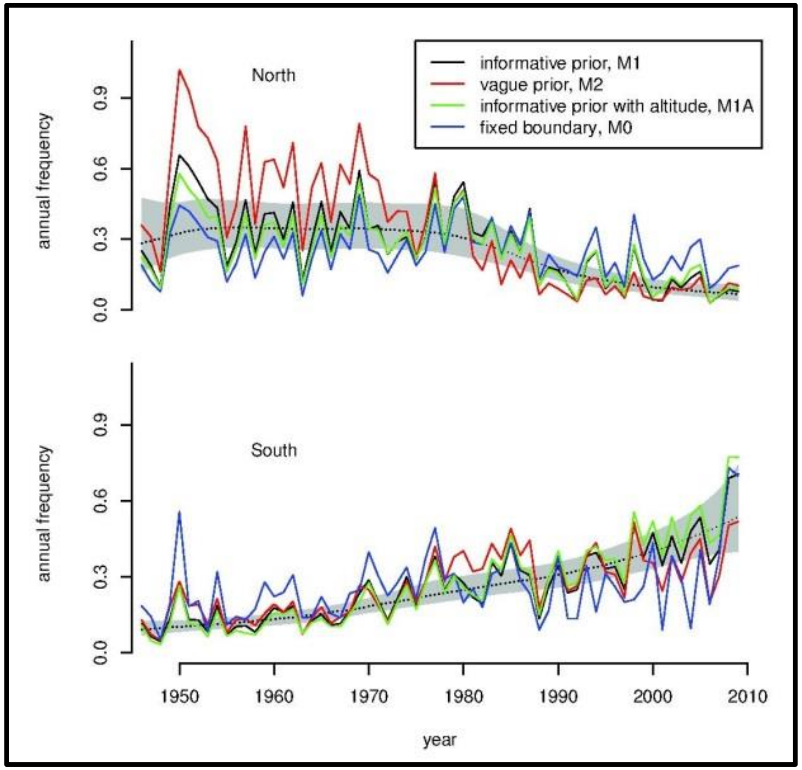
Spatio-temporal patterns and altitudinal gradients

- Spatio-temporal clustering approach for occurrence numbers.
- North/South differences result from complex interactions between predominant atmospheric flows and topography. with a clear altitudinal segregation between two trends: “Low” altitude decrease vs high altitude “transitional” (?) increase (Lavigne et al. 2015).

$$a_{jt} \sim P(\lambda_{jt})$$
$$RR_{jt} = \frac{\lambda_{jt}}{e_j}$$
$$\log(RR_{it}) = \alpha_i + \beta'_{it} + \ldots$$
$$\beta'_{it} = \beta'_t\left[b_{ik}\right]$$
$$b_{ik} \sim dmulti\left(p_{ik}\right)$$
$$p_{ik} = f(x_i)$$



Probability to belong to the “north zone”, with altitude included in the classification, from Lavigne et al. (2015).



Corresponding time trends, from Lavigne et al. (2015). Shows the altitudinal control on north decrease / south increase.

Low (<1000 m) altitude decrease!

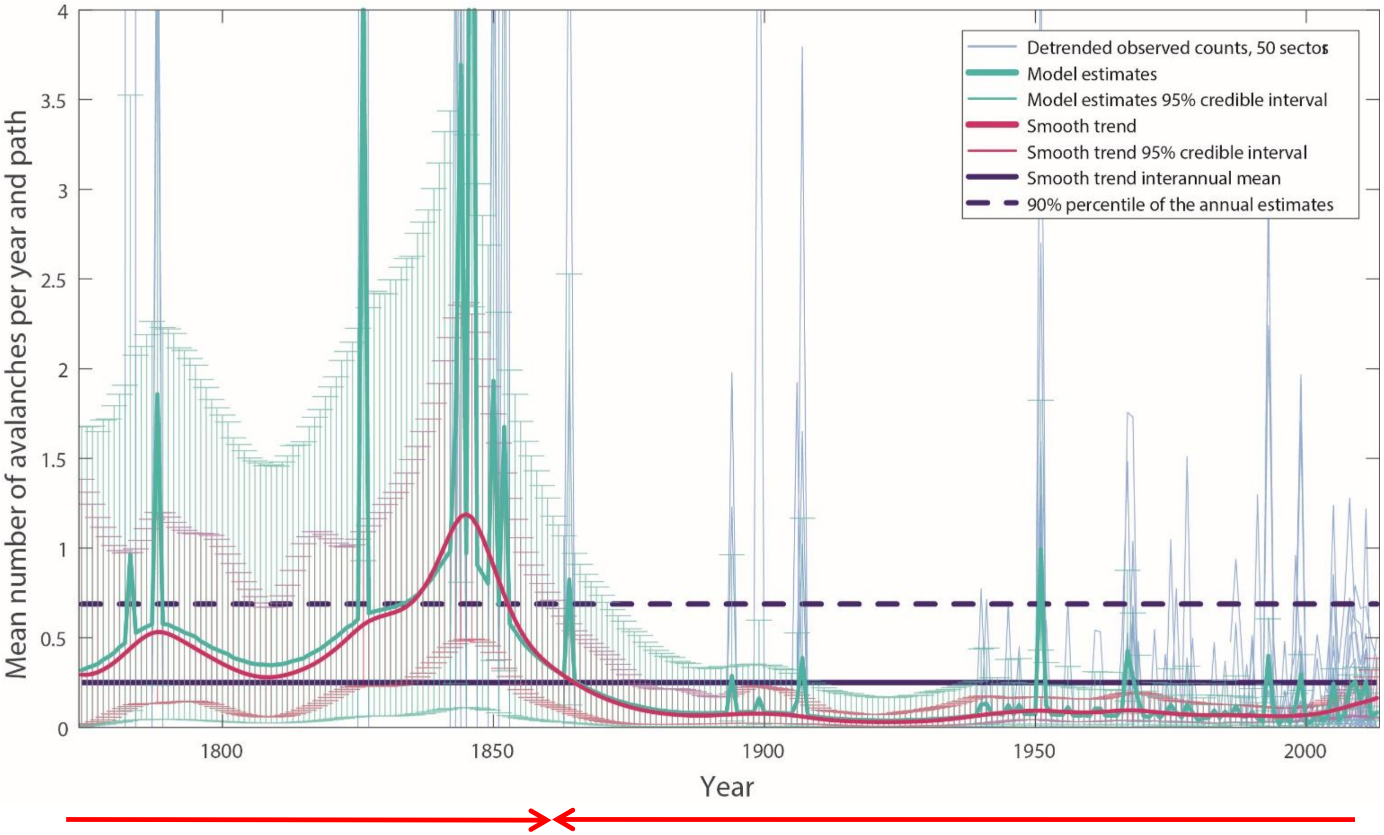
- 240 years of archival data in the Vosges mountains (Giacona et al., NHESS 2017).
- Homogeneisation to take changes in the social context into account

$$\ln(e_{jt}) + v_j + g_t + z_t + \ldots$$

$$e_{it} \propto s_t$$

$$p\left(g \middle| \sigma_g^2, A\right) = \frac{|A|_+^{1/2}}{\sigma_g^{T-2}} \exp\left(\frac{-1}{2\sigma_g^2} g^{tr} A g\right)$$

- Drastic drop at the Little Ice Age termination (Giacona et al., PNAS, 2021)

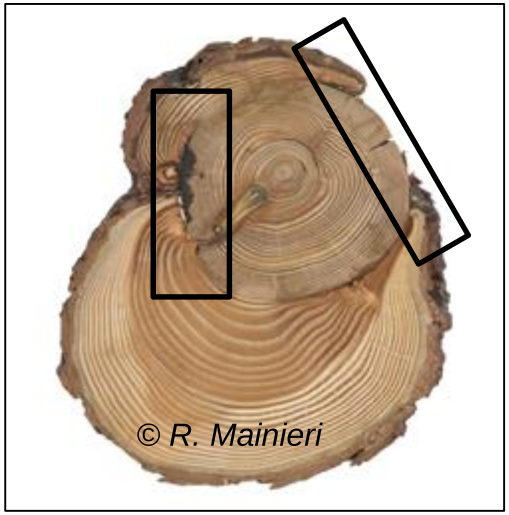


"High activity regime" : ~0.6 avalanches per winter and path

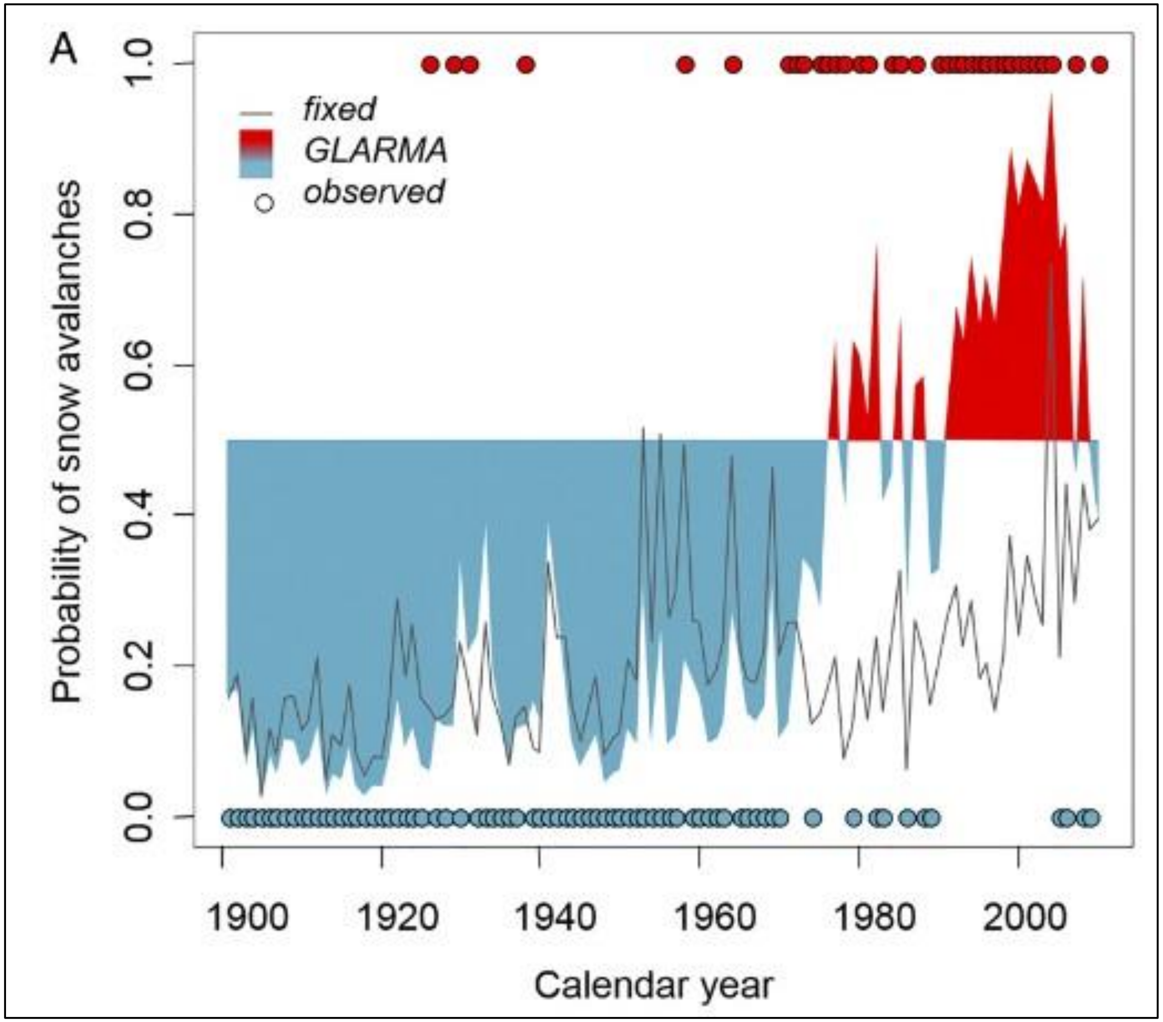
"Low activity regime" : ~0.1 avalanches per winter and path

High altitude activity increase

- 120 years of tree-ring data in the Himalayas (>3000 m asl.).
- Strong increase since ~1975.
- "Classical" GLARMA approach: increase driven by temperature increase and partially related to increase in wet snow avalanching.



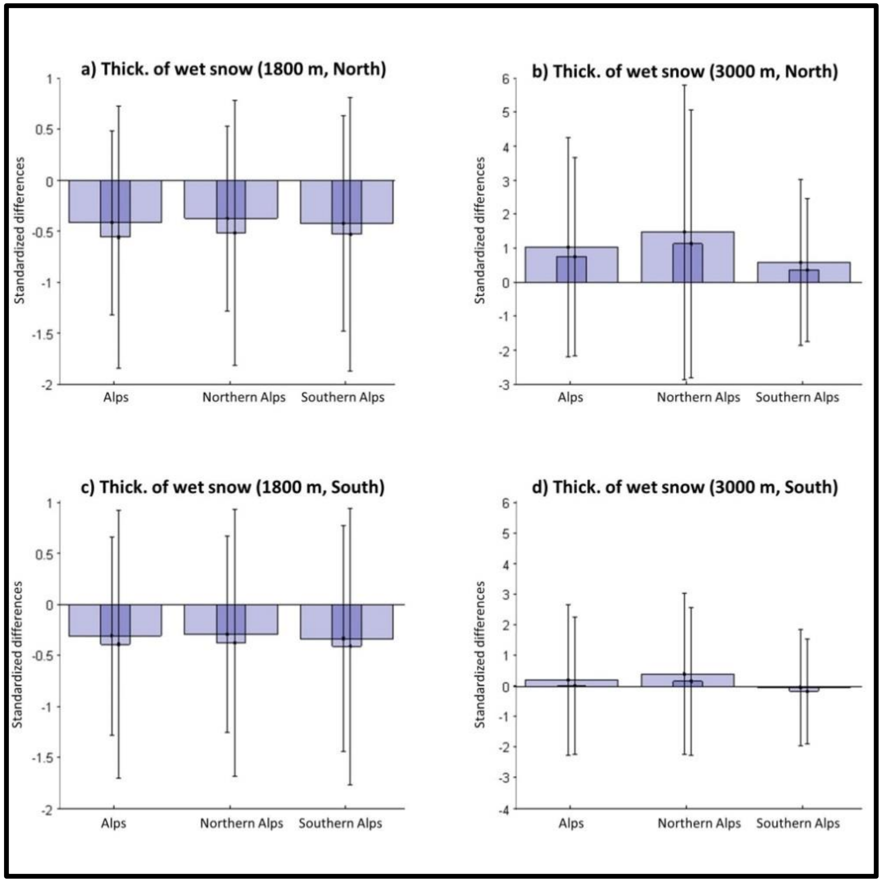
Example of tree cross sections highlighting scars due to avalanches



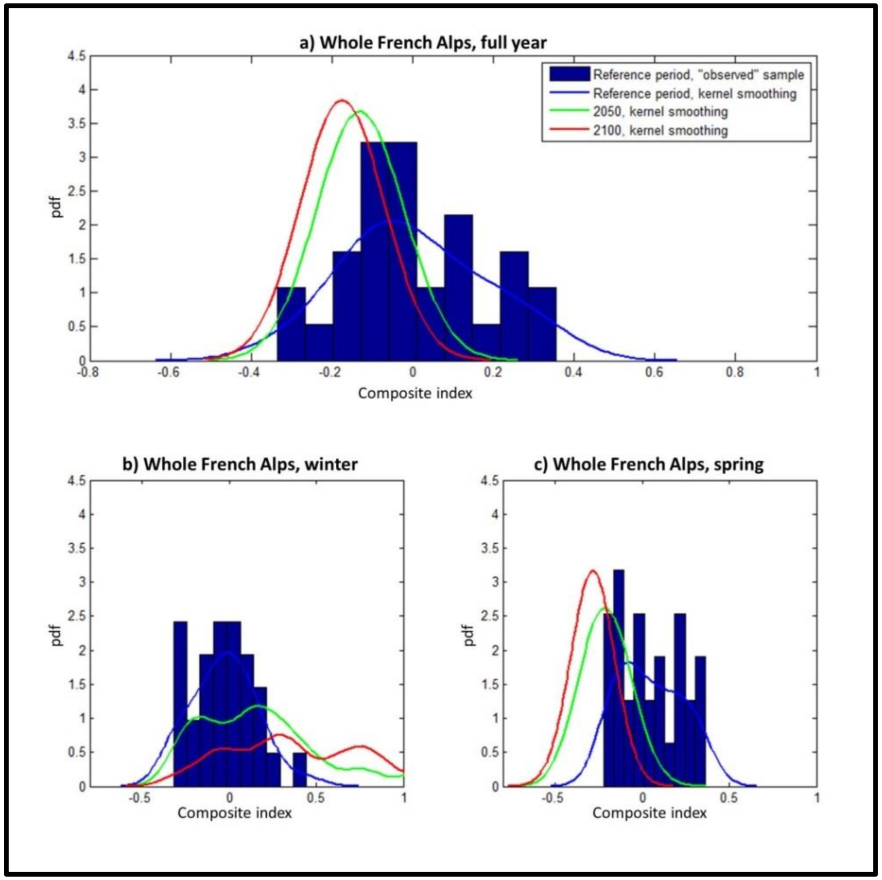
Past changes in avalanche activity in the Himalayas as inferred from tree rings (Ballesteros Canovas… et al., Proc. Natl. Acad. Sci. USA, 2018)

Forecasting inferred relations under future climate

- Future climate scenarios from IPCC AR4 (results to be updated).
- Projected overall and altitudinal/seasonal evolutions consistent with observed past changes.



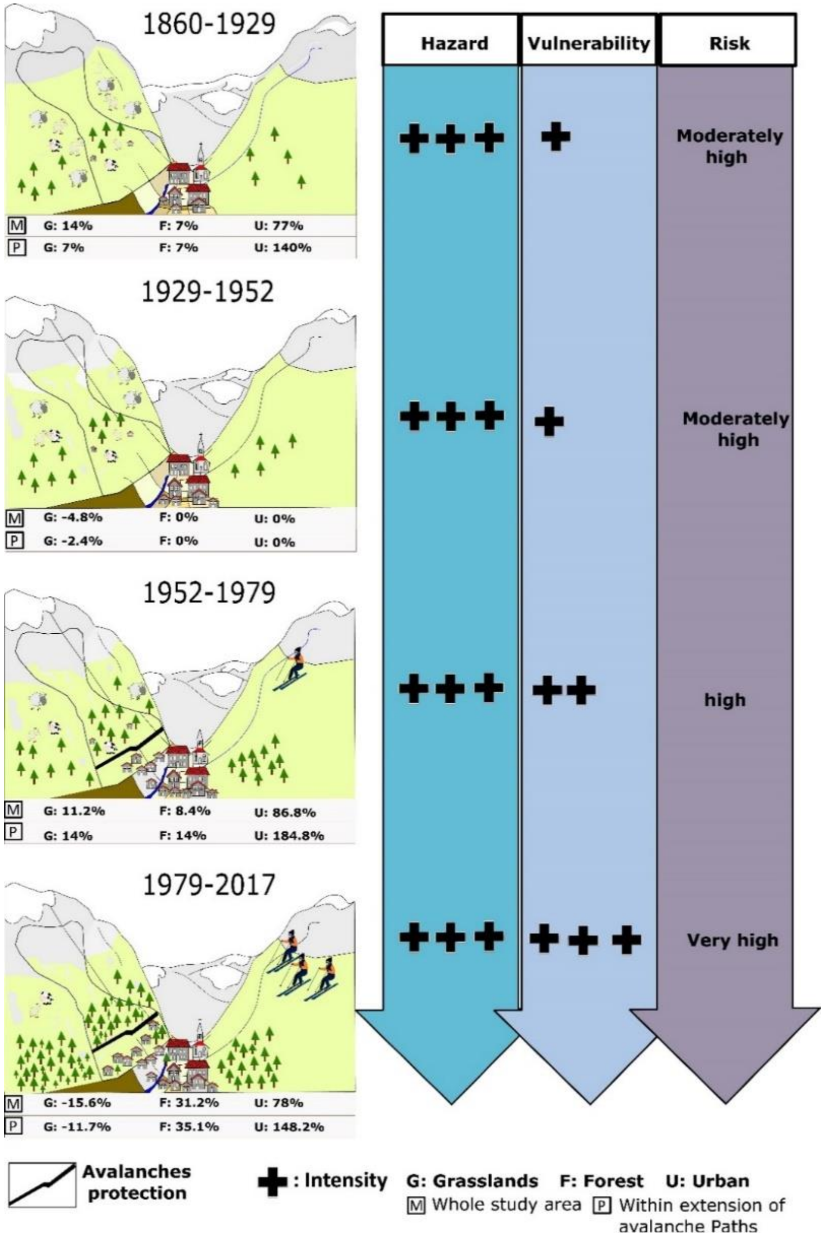
Forecasted future wet snow amounts in the French Alps. Safran-Crocus simulations forced with downscaled IPCC 2007 scenarios. Results are expressed as standardized anomalies with regards to the 1960-1990 period (Castebrunet et al., 2014).



Distribution of the avalanche activity CI over the reference period (1960-90, Castebrunet et al., 2012) and in 2020-50 and 2070-2100. Results are expressed as standardized anomalies with regards to the 1960-1990 period (Castebrunet et al., 2014).

Risk and non stationarity: complex evolutions

- Combination of the evolution of the hazard and elements at risk.
- Very high spatial variability depending on altitude but also on social practices (Zgheib et al, 2022) .
- Example in high altitude valleys: the risk decreased at the turn of the 19th century (agricultural abandonment) but increased over the last decades (tourism and snow cover / avalanche activity still important).
- Clear decrease when climate change combines with afforestation, or even protection works: settlements at the bottom of the slopes can "no longer" be attained.



Co-evolution of land cover, avalanche risk and its components from 1860 to 2017 in the upper Maurienne valley. For each of the four sub-periods, this qualitative model sums-up changes in land-cover and in the different components of avalanche risk to settlements, Zgheib et al. (2021).

Context, concepts and guidelines

Glaciers and glacier risks

Snow extremes and related risks

Snow avalanche risk

Take home message

Take home messages (1)

- **Mountain risks:**
  - Highly non-stationary (up to emergence / disappearance);
  - Strong impacts (“local” scale);
  - Often related to the cryosphere and its progressive shrinkage.

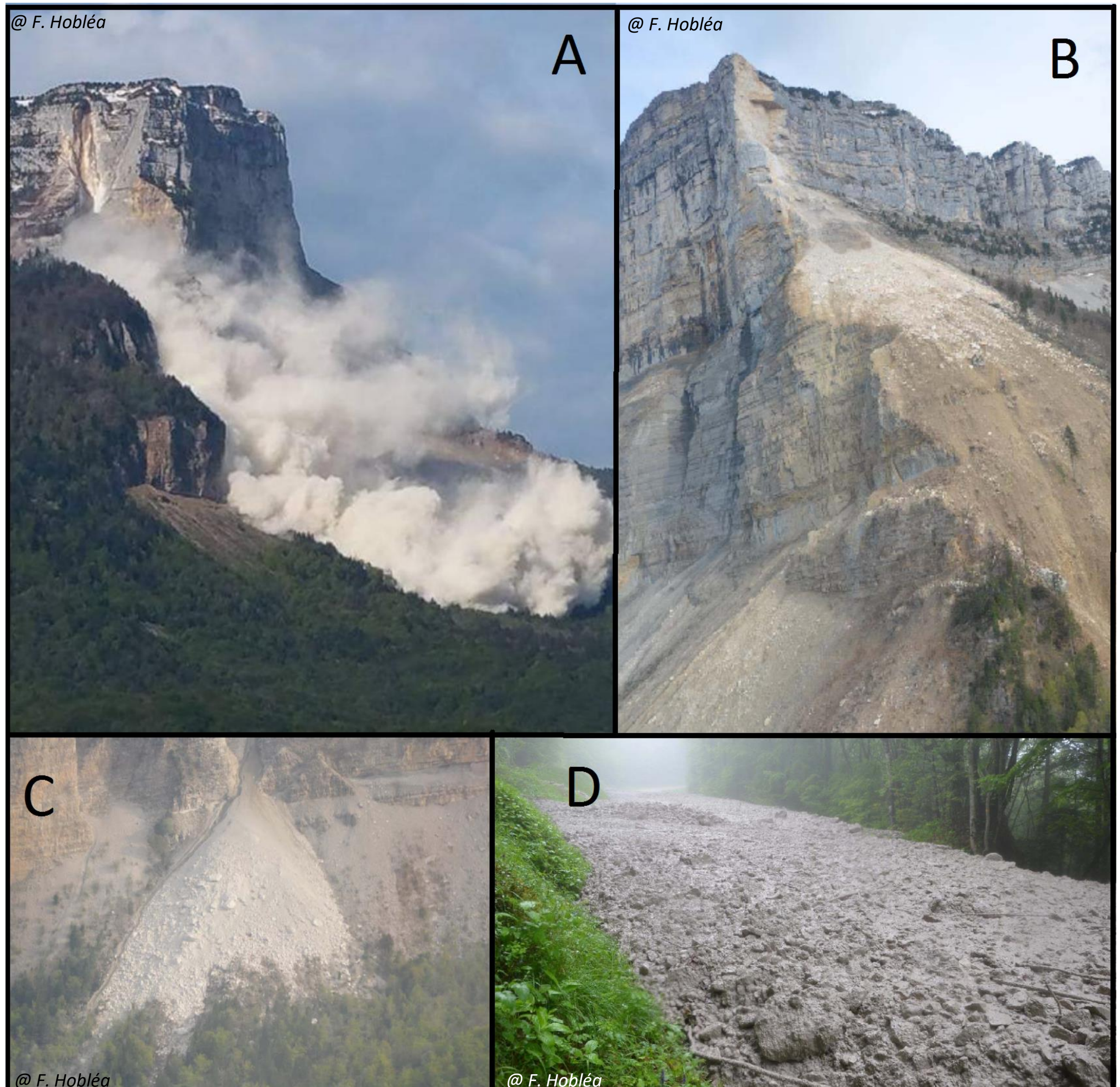
- **Major challenges (classical / sharp questions for statistical modelers):**
  - Combination of process-based and data-based knowledge;
  - Complex space and time dependence structures;
  - Links between scales: downscaling vs. upscaling, global warming vs. local impacts;
  - Extreme values;
  - Machine learning techniques for detection and forecasting;
  - Risk measures;
  - Etc.

Destruction of an hotel by an avalanche in RigoPiano (2017), 29 casualties

Roof collapse due to snowload, Katowice (2006), 65 casualties and 140 injuried

Take home messages (2)

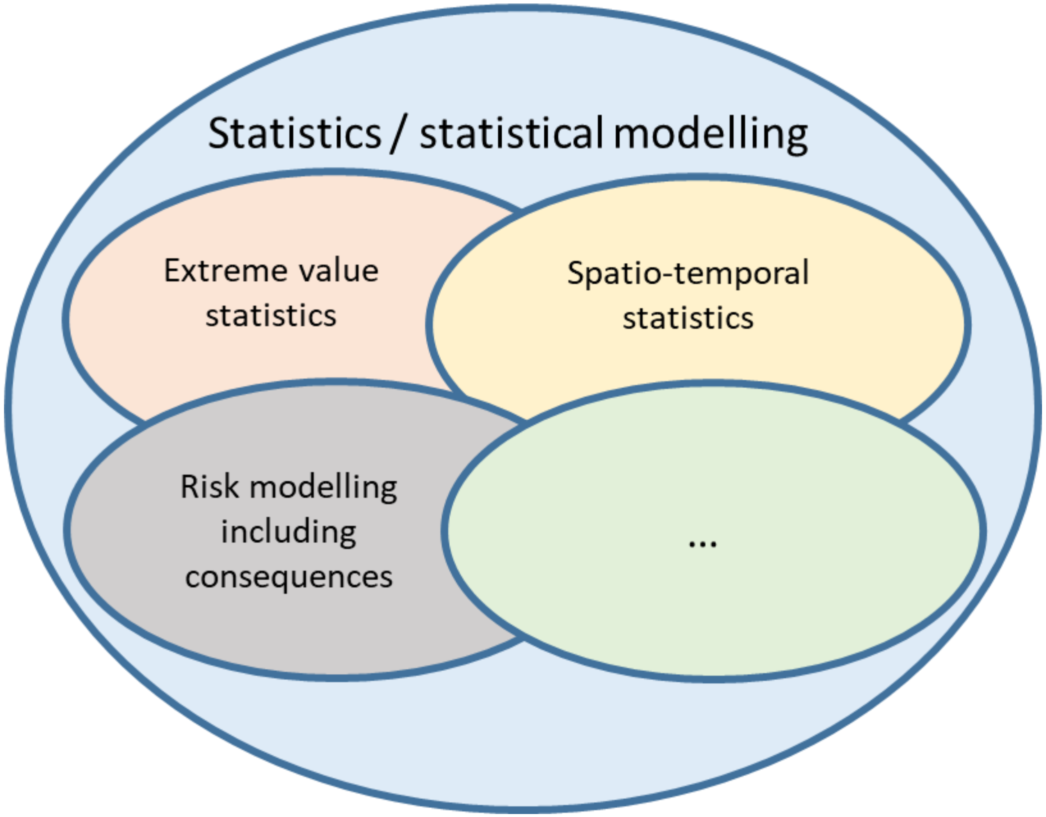
- **This talk:**
  - Focus on risk assessment /modelling;
  - Large needs also on basic physical and social processes (with some stat. challenges!);
  - Quick and incomplete “state of the art” for glaciers, snow and snow avalanche;
  - Many other examples / problems, e.g. rain-on-snow flood event and risk resulting from complex cascading processes.



Cascading processes on Mont Granier, French Alps: Successive rockfall events resulted in accumulation of large amounts of non-cohesive material, which, combined with intense precipitation, led to different debris-flow episodes, putting a road at risk (Eckert, 2017).

Take home messages (3)

- A physically based spatio-temporal model consistent with extreme value theory is desirable, but still far away.
- Existing developments already fulfill several of these requirements, but huge gaps remain.
- A playground for statisticians (inspiring talks to come).



Take home messages (3)

- A physically based spatio-temporal model consistent with extreme value theory is desirable, but still far away.
- Existing developments already fulfill several of these requirements, but huge gaps remain.
- A playground for statisticians (inspiring talks to come).
- But do not walk alone: inter and transdisciplinarity as keys for new and useful developments.
- **Acknowledgements:**
  - For your attention
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