Titre de thèse de doctorat : Changement des risques liés aux extrêmes neigeux : impact sur les infrastructures dans les Alpes françaises dans un contexte de réchauffement climatique

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PhD title: Changes in risks related to snow extremes: Impact on critical infrastructures under a warming climate in the French Alps

Résumé

Les poids de neige extrêmes peuvent surcharger les bâtiments et entrainer des effondrements. Les variables impliquées sont multiples (hauteur et densité de la neige, redistribution par le vent) rendant la prédétermination des valeurs de projet et leur combinaison avec des modèles mécaniques d'impact, d'ailleurs peu développés dans ce domaine, difficiles. Dans le contexte de changement climatique, de fortes non-stationnarités sont déjà identifiées et devraient s'accentuées dans les prochaines décennies, renforçant l'incertitude. Ces tendances (par exemple l'accroissement des hauteurs de neige humide en haute altitude) doivent pourtant être prises en compte dans l'évaluation des risques liés à la neige dans un cadre de planification sur plusieurs décennies.

Cette thèse doit ainsi permettre de mieux évaluer les impacts des extrêmes neigeux sur certaines infrastructures (toits des bâtiments) et l'évolution du risque associé avec le changement climatique, avec une application aux Alpes françaises. Les analyses seront effectuées à partir de longues séries de ré-analyses et de scénarios de projections climatiques haute-résolution (massifs et bandes d'altitude sur toute les Alpes françaises). Dans un premier temps, nous proposons de développer des modèles statistiques de valeurs extrêmes adaptés au cadre spatial non-stationnaire pour les poids de neige, prenant en compte hauteur et densité de la neige et, de façon simple, surcharges dues au vent. Ces modèles, basés sur des processus max-stables, seront ensuite combinés à des modèles mécaniques rustiques permettant d'évaluer le risque d'effondrement d'un toit en fonction de sa technologie. Les modèles de risque ainsi obtenus seront in fine appliqués à l'échelle d'un territoire cible, le Vercors, de façon à quantifier le risque pour différents types d'enjeux à différents horizons. Cette thèse doit ainsi permettre de quantifier certains aspects du risque lié aux extrêmes neigeux qui sont actuellement absents de la littérature (par exemple le risque d'effondrement d'un toit du à la présence d'une congère), et d'évaluer les évolutions probables de ces risques (par exemple les risques liés aux changements de quantité et de densité de la neige lors de fortes accumulations).

Abstract

Extreme snow loads can overload buildings and cause them to collapse. Multiple factors are involved (snow depth, snow density, wind exposure of roof). The determination of design values for snow loads on building structures, in combination with models representing the mechanical response of these infrastructures, is thus a difficult task. Under ongoing climate change, strong non-stationarities

are already identified and are expected to intensify in the next decades. These trends (for example the wet-snow depth increase at high altitude) must be taken into account for the assessment of snow-related hazards in a context of long-term risk management.

This thesis aims at better assessing impacts of extreme snow events on different infrastructures (building roof) and the expected evolutions of the related risks in a context of climate change, with an application in the French Alps. The proposed methodology associates long series of reanalyses and refined snow climate projections available at consistent spatial scales (massifs and altitude bands covering the whole French Alps). Their processing is made with extreme value statistical models implemented within a non-stationary spatial framework. These models, mostly based on max-stable processes, will be combined with rustic mechanical models in order to assess the roof failure susceptibility, depending on the building characteristics. These risk models will be applied to a target territory, the Vercors, considering different risks at stake and different time horizons. Expected results include quantitative insights that have never been investigated (e.g., risk of roof collapse due to a snow drift), and probable changes of these risks (e.g. risks related to changes in snowfall amount and density of extreme snow loads).

1. CONTEXT

1.1. RISK RELATED TO EXTREME SNOWFALLS

Snow extremes can be at the origin of many problems. For example, the blizzard of March 1993 resulted in more than 200 deaths in the United States, 3 million people without power because of downed power lines. The deadliest U.S. snowstorm on record, in 1888, caused around 400 deaths (O'Rourke 1997). Such large snowstorms can also cause structural damage to buildings. After the blizzard in March 1993, one large insurer of industrial facilities reported more than 100 destructions with a total damage of about US$200 million to buildings and their contents. The same insurer reported that in an average year (during the period from 1977 through 1989), it paid for 78 snow and ice-related losses with a total value (property damage and business disruption) of about US$23 million.

Furthermore, rooftop snow can be at the origin of tragic accidents. On 2 January 2006, in the town of Bad Reichenhall, Bavaria, Germany, near the Austrian border, the roof of a 1970s-built ice rink collapsed, possibly under the weight of heavy snowfall, trapping 50 people underneath the rubble (Winter and Kreuzinger 2008). Fifteen people were killed and thirty-two people were injured. Weather conditions in the area were extremely severe, an avalanche having killed three people nearby earlier in the day. The same month, on 28 January 2006, the roof of one of the buildings at the Katowice International Fair collapsed in Chorzów / Katowice, Poland. There had been 62 dead as well as about 160 injured (*The New York Times* 2006). Poland was at that time experiencing very cold weather with heavy snow.

In France, a major meteorological event illustrating the dramatic impacts of snow extremes occurred on 30-31 January 1986 over Roussillon (Vigneau 1987). Very dense and abundant snowfalls led to important snow loads over a very large region (for example 110 cm in Génolhac at an elevation of 540 m, 150 cm in Fourtou at an elevation of 670 m). While similar amounts of precipitation can be observed in Mediterranean regions, this thick snow cover was mainly composed of sticky snow and can be considered as exceptional. This snow load caused major damages to power lines, most of the households being left without power (during more than one week for 5% of the population). Major transport network disruptions, mainly due to avalanches, isolated entire villages and ski resorts during several days. 13 deaths were recorded, among which two persons killed by an avalanche, and one father and his child who tried to reach their home by foot and froze to death. Numerous buildings collapsed due to the weight of the snow. The roofs were not designed to handle a snow load formed by 30 cm of sticky snow, equivalent to a pressure of more than 150 kg/m^2.

The assessment of extreme snowfalls is thus an important consideration for the design of buildings where snow accumulations can be important. More precisely, the risk of roof collapse is mainly due to the weight of snow on the roof, which is a combination of snow volume and density. Moreover, as ice and snow tend to accumulate on the down-wind side of a roof (FEMA 2013), especially during high winds, the uneven distribution of the snow load can be an aggravating factor.

1.2. MOUNTAIN SNOW CLIMATE CHANGE

The warming in Europe has been marked, and accelerated over the 1985–2000 period (IPCC 2014). Mountainous areas being very sensitive to climate change (Beniston et al. 2017), temperatures have, for example, increased twice as much as the global average since the late nineteenth century in the European Alps (e.g. Beniston 2005; Auer et al. 2007). At low and moderate altitudes (800 – 2000m), air temperature frequently oscillates around the water freezing temperature (0°C) in winter, making snow related variables particularly accurate markers of this warming. Significant decreasing trends over the past decades of snowfall, snow cover amounts and durations, etc. are documented at low and mid-altitudes in most of European mountain ranges, whereas concomitant changes at high altitudes remain much weaker (e.g. Falarz 2002; Laternser and Schneebeli 2003; Marty 2008; Durand, Giraud, et al. 2009; Valt and Cianfarra 2010).

In the French Alps, total precipitation amounts (rain and snow) are expected to remain quite stationary. The evolution of snow precipitation amount and snowpack characteristics is thus strongly related to the temperature increase and the topography (in particular, a reduction of the dry snowpack and an increase of the wet snowpack, see Castelbrunet et al. 2014). Overall, while expected changes are strong for the end of the 21st century, they are already significant for the mid-century. Changes in winter are less important than in spring, but wet-snow conditions are projected to appear at high elevations earlier in the season. At the same altitude, the southern French Alps will not be significantly more affected than the northern French Alps, which means that the snowpack will be preserved for longer in the southern massifs which are higher on average.

Under ongoing climate change, atypical and more frequent natural hazards due to snow extremes are expected to occur (Beniston et al. 2017). However, as evolutions of extreme snow precipitation amounts and snowpack characteristics will happen concomitantly, different effects can possibly balance each other out (for example less snow in volume but more wet snow). Evolutions of natural hazards due to snow extremes are thus hard to predict and prone to strong uncertainties.

2. STATE OF THE ART

2.1. EXTREME VALUE MODEL ACCOUNTING FOR NON-STATIONARITY IN SPACE AND TIME

As for other geophysical variables such as rainfall or river discharge for which high percentiles of the distribution are key quantities, extreme value theory (EVT) (Coles 2001) is a suitable framework to work with. Specifically, it is now well known that the so-called generalized extreme value (GEV) distribution is an adequate model for block maxima (e.g., annual maxima), allowing sound extrapolation beyond the highest observed value. Examples of this modelling framework on snow related quantities are Blanchet and Lehning (2010) on snow depth and Sadovský et al. (2012) on exceptional snow falls.

A direct extension of the univariate extreme value theory deals with extremes in space, for which max-stable processes (De Haan 1984) are particularly suitable. Following several theoretical developments (Smith 1990; Schlather 2002), applications of max-stable processes to geophysical variables have become popular in the last decade. An important breakthrough was the use of composite likelihood maximization techniques by Padoan et al. (2010), who showed how max-stable processes could be fitted to extreme rainfall in the U.S. Concerning snow related quantities, this framework has already been applied by Blanchet and Davison (2011) to extreme snow depths in Switzerland and by Gaume et al. (2013) to extreme snowfall and subsequently to avalanche slab depths in the French Alps.

As mentioned above, due to the influence of temperature on the rain/snow partitioning of precipitation, snow-related variables are particularly sensitive to the recent warming (Falarz 2002; Durand, Giraud, et al. 2009; Valt and Cianfarra 2010). Significant decreasing trends were highlighted in extreme snowfall and snow depths in Switzerland by Marty and Blanchet (2012). In France, while several studies (see, e.g., Neppel, Pujol, and Sabatier 2011; Tramblay et al. 2013; Vautard et al. 2015) have been devoted to the analysis of the stationarity of rainfall extremes, such analyses are almost absent concerning snow extremes. One exception is Nicolet et al. (2016), who show how the spatial dependence structure in extreme snowfall in the French Alps has evolved over the last decades, with a significant negative trend in the strength of extremal dependence for large distances (more than 100 km taking into account anisotropy). However, the nonstationary of extreme snowfalls at each station is not represented in their model[1]. Additional knowledge about the evolution of extreme snow-related quantities is thus required. The same holds true for projections of heavy drifting snow events resulting from wind gusts. To date, the combined evolution of extreme snow amount, type (dry, wet), and density in the French Alps remains virtually unknown (Beniston et al. 2017).

2.2. FROM A STATISTICAL MODEL TO AN IMPACT MODEL

Risk assessment of natural hazards is often performed using reference events related to high return periods (typically extreme flood quantiles associated to 10^3 years or even 10^4 years for applications to dam safety). These standard engineering practices are a simple mean to handle the complex and multivariate nature of geophysical variables (volumes, durations and peak flows for floods, volumes and runout distances for snow avalanches). However, such methods do not explicitly take into

[1] It must be noticed that the evolution of the spatial dependence structure in extreme snowfall shown in Nicolet et al. (2016) is still significant when marginal distributions are fitted on moving time windows.

account the elements at risk. In recent years, many authors from a variety of fields have tried to overcome these limitations with quantitative risk evaluations including the cost related to building or infrastructure damage.

In the field of natural hazards, risk is generally defined by the product of hazard and vulnerability, i.e. a combination of the damageable phenomenon and its consequences. Concerning the risk related to snow-related quantities, Eckert at al. (2012) review quantitative risk and optimal design approaches in the snow avalanche field. Recent applications motivate the computation of the risk as an expected damage, i.e. as the expectation of the consequences of avalanche activity for the whole system at risk (persons, traffic roads, a full mountain village, etc.). This approach is applied by Sadovský and Sýkora (2013) for the assessment of accidental snow loads, using combinations of statistical models of exceptional snowfalls and very simple design situations of industrial buildings.

To date, impact models relating socio-economic consequences to extreme snow events (e.g., roof collapse probability as a function of snow mass and roof technology) remain oversimplified. Roof snow load is not directly related to ground snow load and depends on multiple factors, such as wind exposure of the roof, wind intensity (Meløysund et al. 2007) and thermal condition of the building (FEMA 2013). Non-stationarities in snow properties (for example the wet-snow depth increase at high altitude) must also be taken into account for the assessment of snow-related hazards. However, more detailed knowledge about the evolution of extremes in snow properties is necessary (Beniston et al. 2017). The moisture content or density of snow is needed, for example, when evaluating the probability for a particular infrastructure to collapse under future extreme snow loads (Sadovský and Sýkora 2013). Furthermore, the development of simple and robust models representing the mechanical response of these infrastructures under extreme snow loads is needed (Rózsás 2016). At the present time, how these snow-related hazards will evolve in the next decades is an open question. Efforts are required to combine snow-climate and vulnerability assessment expertise (Favier et al. 2014) if realistic future projections are to be made.

3. METHODOLOGY

3.1. ASSESSMENT OF PAST AND FUTURE CHANGES IN SNOW EXTREMES

In a first part of this thesis, a renewed complete assessment of past and future evolutions of snow-related quantities will be performed for the French Alps using direct measurements, re-analysis and snow climate projections. Many variables are important for the assessment of snow-related hazards (for example the wet-snow depth). Therefore, these trends must be assessed for all these quantities, including snowfall amounts, snow depths, and snow water equivalents.

In order to complete the measurements provided by the meteorological stations in the French Alps, which usually consists in short series (typically 20-30 years), this first analysis will be carried out using SAFRAN re-analysis. These re-analysis are obtained using the ‘‘SAFRAN’’–Crocus–‘‘MEPRA’’ (SCM) model chain (Durand, Laternser, et al. 2009; Durand, Giraud, et al. 2009), and are available at consistent spatial scales (massifs and altitude bands covering the whole French Alps) In addition, refined snow climate projections are also available at the same spatial scales. These snowpack scenarios are modelled across the French Alps using dynamically downscaled variables from different Regional Climate Models (RCM), for different emission scenarios, and for the 21st century. These variables are statistically adapted to the different elevations, aspects and slopes of the Alpine massifs. In addition, the resulting scenarios of precipitation, temperature, wind, cloudiness, longwave and shortwave radiation, and humidity are used to run the physical snow model CROCUS (Vionnet et al. 2012) and simulate snowpack evolution over the massifs studied.

3.2. NON-STATIONARY STATISTICAL MODELS FOR VARIOUS SNOW EXTREMES

The second phase will be dedicated to the development of extreme value models applied to extreme snow-related quantities. Following Gaume et al. (2013), extreme value statistical models will be implemented within a non-stationary spatial framework mostly based on max-stable processes. Different models with smooth trends (e.g. B-splines) will be considered to represent the spatial evolution of the parameters, including orographic effects.

In addition to these spatial evolutions, the full extreme value model will incorporate the trends identified during the first past of thesis, using for example representation of the model parameters as a function of time. Finally, a significant extension of this spatio-temporal extreme value model can be foreseen if temporal evolutions of the dependence structure identified in Nicolet et al. (2016) are also included.

The final result will consist in design maps for different quantities at stake (ground snow depth, ground snow load), different return periods (e.g. 100 years) and different time horizons (e.g. 2050, 2010). These results constitute a powerful operational tool for long-term risk management, especially to establish hazard maps, and will be used as inputs of impact models.

3.3. IMPACTS ON CRITICAL INFRASTRUCTURES UNDER CURRENT AND FUTURE CLIMATE

The third part of this thesis will focus on explicit risk assessment of snow extremes for different infrastructures. The methodology will be developed for an application where static loads are at the origin of critical damage to infrastructures: collapse of buildings due to snow overloads. Impact models will be applied to a target territory, the Vercors, considering different risks at stake (different building characteristics) and different time horizons.

Roof snow load is related to ground snow load, but also depends on the quantity of snow transported by the wind (Meløysund et al. 2007), possibly leading to unbalanced snow loads and greater risk to the roof structural system than a uniform snow load (FEMA 2013). Furthermore, snow transport theory also indicates the quantity of snow transported depends on snow type (type of snow particles, snow density). Using SAFRAN re-analysis and design values of ground snow loads, possible scenarios of extreme roof snow loads will be proposed, possibly with important snow drifts, based on local topography, wind exposure and average wind velocities during snow events.

The risk assessment of roof collapse under extreme snow loads has not been studied in depth in the literature, and only coarse results are available (Sadovský and Sýkora 2013; Croce et al. 2017). The proposed developments will take into account the multivariate aspects of the roof snow loads, for example snow density, through the quantity of wet and dry snow, and the presence of snow drift. Applications will be based on standard buildings in mountainous areas and different building characteristics. This part of the work will be carried out in collaboration with INSA Lyon (following previous studies on avalanche risk evaluation and protective dam design using extreme value statistics). In a context of climate change, it can be expected that the increased proportion of wet snow will lead to a greater risk of collapse in the future.

The main application will be done for a target territory, the Vercors. Different risks at stake will be considered, based for example on typical building characteristics, or on existing buildings available in cadastral plans. The risks will be assessed for different time horizons, and different assumptions can possibly be made to evaluate future risks (using current design of structures, i.e. ISO 4355, or stricter standards).

4. Planning:

- **Sep 2018 – Sep 2019:** Acquisition and first analyses of observations, re-analyses and projections. Assessment of past and future changes of snow extremes.
- **Oct 2019 – Sep 2020:** Developments in non-stationary spatial extremes. Production of maps of different snow-related quantities (snowfall, snow depths, snow density) for different return periods and different time horizons. Development of required mechanical models of cable and roof failure as function of snow mass and infrastructure technology in collaboration with INSA Lyon.
- **Oct 2020 – Sep 2021:** Explicit coupling of snow extremes with impact models on critical infrastructures: evaluation of individual risks and total risk on the targeted areas at different temporal horizons.

5. Scientific production

5.1. Publication strategy

The different aspects of the work will be published in international high quality journals:

- “Analyses of past and future changes in snow extremes” Climatic change (IF=3.3 in 2015)
- “Statistical models for snow extremes: non-stationarities in space and time” Water Resources Research (IF=4.4 in 2016)
- “Impacts of snow extremes on critical infrastructures under current and future climate” Cold Regions Science and Technology / International Journal of Reliability, Quality and Safety Engineering.

5.2. Potential applications

- Design maps for different snow-related quantities (snow depth, snow load), for different return periods and different time horizons in the French Alps.
- Vulnerability maps for different risks at stake (different building characteristics) and different time horizons in the Vercors massif.

These products will be made available for practitioners, which should, for example, assist them for the preparation of local disaster risk reduction strategies.

6. Organisation :

6.1. Supervision

- Guillaume Evin (IRSTEA - ETGR)
- Nicolas Eckert (IRSTEA - ETGR)

6.2. Research Unit

IRSTEA - ETGR - Torrent erosion, snow and avalanches

6.3. Required qualification

Applicants should have a master in statistics or applied mathematics / probabilities. Experience in using numerical codes would be appreciated as well as interest for environmental and multidisciplinary issues. Applicants should be fluent in oral and written English. Knowledge of a programming language (e.g., R, Matlab) is required. An engineering degree would be advantageous. The job is offered with no restriction on age, sex or nationality, in accordance to French law.

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