Proposition de thèse de doctorat : Retro-trajectoires du risque avalancheux résultant de changements climatiques et sociaux-environnementaux sur des sites choisis des Alpes françaises

PhD proposition: Backward trajectories of avalanche risk resulting from climatic and socio-environmental changes on selected hot spots of the French Alps

Sujet propose par l'unité Erosion Torrentielle Neige et Avalanches (ETNA), Irstea Grenoble / Université Grenoble Alpes (UGA) et porté par Nicolas Eckert, chercheur-ingénieur de l'unité ETNA et Samuel Morin, directeur du Centre d'Etude de la Neige

Abstract

Long term changes in snow avalanche risk result from combined changes in its environmental (climate, forest ecosystems) and social (land use, social practices, tourism, etc.) components. In reverse, changes in avalanche risk finely traduce the rapid evolution of a sensitive system. Combining tree-ring reconstitutions, historical archives and instrumental data and analyzing these using advanced statistical tools may improve our knowledge and understanding of these changes. As a contribution to this effort, this PhD will fill the gap between fully empirical approaches and more physically based numerical simulation tools already working in the stationary case. Specifically, a statistical numerical framework explicitly coping for non-stationarity in avalanche dynamics will be developed. It will be used to reconstruct, on selected hot-spots (specific avalanche paths mostly located in Haute Maurienne and Quyras), past avalanche events that occurred mostly over the last 200 years. From this, changes in local magnitude-frequency relationships will be inferred and, combined with elements at risk and damage susceptibility relations, changes in the related risk will be evaluated. This should provide new insights of unprecedented precision regarding past changes in avalanche risk, their climatic control, and their co-evolution with social practices and forest ecosystems. For instance, we should be able to highlight different behaviors of flow dynamics at the climax of the *Little Ice Age* and for the warmest, most recent, decades, thus refining our knowledge on the influence of predominant control variables on snow rheology. Also, we expect better understanding of the protective effect of forest cover, and how its interaction with avalanche activity results (or not) in an equilibrium state. Hence, even if the PhD will mostly involve applied mathematics, it will be a contribution to a wider interdisciplinary initiative involving historians, climatologists and ecologists in addition to statisticians and snow and avalanche specialists.

2 Detailed description of the work

2.1 CONTEXT AND STATE OF THE ART

2.1.1 MOUNTAIN SNOW CLIMATE CHANGE

The warming in Europe since the end of the Little Ice Age (end of *LIA*, ~1850) has not been constant, with periods of slower temperature increase or even cooling. Yet, overall, it has been marked, and accelerated over the 1985–2000 period (IPCC, 2013). Mountainous areas being very sensitive to climate change (e.g., Beniston et al., 1997), temperatures have, for example, increased twice as much as the global average since the late nineteenth century in the European Alps (e.g. Beniston, 2005a; 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. could therefore be documented at low and mid-altitudes in most of European mountain ranges, whereas concomitant changes at high altitudes have remained much weaker (e.g. Falarz, 2002; Laternser and Schneebeli, 2003; Marty, 2008; Durand et al., 2009; Valt and Cianfarra, 2010; Serquet et al., 2011; Morán-Tejeda et al., 2013).

2.1.2 RELATED CHANGES IN AVALANCHE ACTIVITY

Snow has key impacts on the water cycle, ecosystems and many geomorphological processes. Among them, snow avalanches are a redundant natural hazard as soon as slope is sufficient. Loss of lives (Ammann and Bebi; 2000), property damages (Eckert et al., 2010a), and disruption of transportation corridors (Léone et al., 2014) are frequent, for instance in communities for which the ski industry is a major source of income (Elsasser and Buerki, 2002; Gonseth, 2013). As a phenomenon directly governed by snow and weather variables, snow avalanches may intuitively be strongly affected by warming. Hence, adaptation to changes in potentially catastrophic events may be a major concern, as one of the most striking example of emerging/changing risks in the mountain cryosphere (Keiler et al., 2010; Huggel et al., 2012; Stoffel et al., 2013). Yet, to date, only few studies, concerning the recent decades, have provided evidences of clear changes in real avalanche data from systematic observational records, and they concern the recent decades only (IPCC, 2012). Specifically, in the French Alps, marked temporal patterns in occurrences and runout altitudes could be demonstrated over the 1946-2009 period (Eckert et al., 2010b; 2010c; 2013). Changes in different types of avalanche activity (wet/dry and or with/without a powder part) have been reported even more recently (Pielmeier et al., 2013; Eckert et al., 2013; Naaim et al., 2016). Most of other existing studies did not demonstrate any significant changes (e.g., Schneebeli et al., 1997; Laternser and Schneebeli, 2002).

A reason for this limited knowledge is the lack of sufficiently long and complete systematic records of past snow avalanches, which makes standard methodologies for trend detection (e.g. Burn and Hag Elnur, 2002) hard to implement. Another reason is that, even if good relations with large scale atmospheric patterns (Keylock, 2003) and local scale snow and weather drivers (Smith and McClung, 1997a;b; Castebrunet et al., 2012) exist, avalanche activity's response to climate change is not necessarily univocal. For instance, different effects potentially compensate each other's. Warming means, in mean, less snow and, therefore, less avalanche triggers, but the documented increasing number of warm winter spells (Beniston, 2005b) may destabilize the high altitude deep snowpack. Hence, part of the complexity is attributable to the elevation dependent warming patterns (Rangwala and Miller, 2012) and subsequent altitudinal gradients in snow variable changes. Typically, Lavigne et al. (2014) has demonstrated in the French Alps that the overall predominant temporal pattern to change over the last decades is the sum of a marked decreasing component at low altitudes, in agreement with the snow cover reduction, and of an increasing component at high altitudes potentially related to more intense heavy snowfall (López-Moreno et al., 2009) as soon as temperature remain below the freezing level, and/or to the increasing winter temperature variability (Beniston, 2005b).

2.1.3 AVALANCHE FLOW DYNAMICS AND THEIR CLIMATIC CONTROL

Even if correlations between snow avalanche series and weather covariates can be highlighted, such links do not necessarily demonstrate causality. One thus needs to go deeper into the climatic control of snow avalanche dynamics (Bartelt et al., 2012; Naaim et al., 2013). Snow avalanche flow has been widely investigated over the last decades with field experiments and numerical modelling (Ancey et al., 2006). Evidence obtained on full-scale experimental slopes (Vriend et al., 2013) show a typical vertical stratification of the flow. The framework of continuum mechanics (Savage & Hutter, 1989) can reproduce these observations with 3D models (Issler, 1997). Considering only the dense layer of avalanches allows a shallow water approximation to be used (Bartelt et al., 1999, Naaim et al. 2004), leading to state-of-the art models for hazard mapping. However, even for the dense layer, knowledge concerning the mechanical behaviour of snow during motion remains scarce. Experimental approaches (Casassa et al., 1989) and small-scale snow flows (Rognon et al., 2008) have shown that friction seems to increase with square velocity, which is in good agreement with Voellmy's (1955) proposal, but the rheological behaviour that can be deduced from these experiment remains ad-hoc, with no direct inclusion of climate control variables. This renders on-site calibration using available archival records unavoidable to predict high return period events for risk assessment purposes (Ancey & Meunier, 2004), and even makes such predictions questionable in the context of climate non-stationarity.

Bayesian probabilistic calibration methods have been proposed recently to overcome the technical difficulties caused by data limited in quantity, non-explicit in nature, and by friction parameters too numerous for a single solution of the inversion problem (Ancey et al., 2003). The reconstruction of past activity and prediction of high return period avalanches (Barbolini & Keylock, 2002; Eckert et al., 2008; 2010d; Meunier & Ancey, 2004) with respect to available data (Ancey, 2005; Eckert et al., 2009; Gauer et al., 2009) is straightforward. Interestingly, it was shown recently that such an approach provides results extremely close to those derived from a refined tree-ring reconstruction (Schläppy et al., 2014). However, in all this work, past events where reconstructed and the relationship between runout distance and return period derived under the strong underlying assumption of stationarity, and also in agreement with the rather short temporal frame investigated.

2.1.4 DOCUMENTING AVALANCHE ACTIVITY CHANGES OVER LONGER TIME SCALES AND LINKS TO SOCIO-ENVIRONMENTAL TRAJECTORIES

To document past changes in snow avalanche activity over longer time scales, recourse to indirect data from sedimentology (Bikra and Sæmundsson, 1998), lichenometry (McCarroll et al., 1995; Nesje et al. 2007) or dendrogeomorphology (tree ring data, Corona et al., 2010; Schläppy et al. 2013) is possible. These proxies suggest that major avalanches of the type that occurred during the *LIA* have not been encountered in recent decades in the Alps (Jomelli and Pech, 2004). However, even if the longest tree-ring chronicle of past avalanche events acquired was able to go back to the 14th century (Corona et al., 2013), due to the amount of field work required, such data have been published for a low number of paths only, to date, presumably no more than a few dozen worldwide. Additionally, their length and completes is highly dependent on the age and characteristics of forest stands (Bebi et al., 2009), the latter resulting from interacting climate factors and social practices (forest exploitation, grazing, etc.).

In between data from systematic records and indirect paleo-data, historical information extracted from archival sources provide insight into past avalanche activity and may be seen as a promising way to fill the gaps with strengths related e.g. to a good-dating control and a high time-resolution (Pfister, 1999). Such a tough but rewarding approach is now often adopted for many natural hazards, e.g. for retrieving major floods having occurred before systematic discharge measurements (Stediger and Cohn, 1986; Naulet et al., 2005; Payrastre et al., 2011). In the snow avalanche field, a few attempts have been made (e.g. Laely, 1984; Fliri, 1998; Granet-Abisset and Brugnot, 2002), but generally at the path or township scale for risk assessment purposes rather than over an entire and climatically coherent mountain range. As an exception, Giacona et al. (2016a) compiled historical references to avalanche events in the small Vosges massif, and were able to identify ~700 avalanches back to 1780. Yet, exploitation of such rare datasets for snow-climate inference is difficulty (Giacona et al., 2016b). Indeed, Historical documentary information tends to emphasize extreme events as these were generally the most important phenomenon that deserved recording (Jones et al., 2008). Furthermore, far in the past, only a few events can be retrieved since memory has focused only from those catastrophic that had direct impacts on either property or human lives (Pfister, 1999).

Hence, exploitation of nonconventional data may be an important source of progress to enlarge the spatio-temporal coverage of instrumental series in the snow and avalanche field. However, taking the intrinsic specificities of such data into account is then crucial but difficult. Specifically, their link to socio-environmental changes is direct, making a contextualization step unavoidable. As a reward for this additional work, changes in avalanche risk inferred from historical and environmental data may, in turn, traduce finely the rapid evolution of a sensitive socio-environmental system.

2.2 METHODOLOGY AND MILSESTONES

2.2.1 A CONTRIBUTION TO A WIDER MULTIDISCIPLINARY APPROACH

On this basis, this PhD will fill the gap between fully empirical approaches and more physically based numerical simulation tools already working in the stationary case to investigate how long term changes in snow avalanche risk result from combined changes in its environmental (climate, forest ecosystems) and social (land use, social practices, tourism, etc.) components. Specifically, a statistical numerical framework explicitly coping for non-stationarity in avalanche dynamics will be developed. It will be used to reconstruct, on selected hot-spots (specific avalanche paths mostly located in Haute Maurienne and Quyras), past avalanche events that occurred mostly over the last 200 years (a few even older ones will be considered, when possible). From this, changes in local magnitude-frequency relationships will be inferred and, combined with elements at risk and damage susceptibility relations, changes in the related risk will be evaluated.

The PhD will mostly involve applied mathematics (advanced statistical modelling coupled with numerical simulations of avalanche flows). Yet, it will be a key contribution to a wider interdisciplinary initiative involving historians, climatologists and ecologists in addition to statisticians and snow and avalanche specialists. Resource people from all these disciplines will be associated in the PhD's committee.

According to state of the art, investigations of how long range evolutions of climate, ecosystems and society drive the phenomena and the risk are very rare in the snow avalanche field. In addition, existing ones are often biased towards a limited number of historical records and statistical procedures insufficient to exploit them. To this end, this PhD will benefit from an exceptionally rich data set currently acquired and analysed, without recourse to avalanche simulations, in the framework of the AGIR-PEPS RARETE project. This data set, built on the selected hot spots, includes:

- Composite avalanche activity and risk chronologies summing up unpublished tree-ring reconstitution and historical archives with instrumental data.
- Extensive climate reconstructions. They range from refined snow-climate-instability indexes reanalyses covering the last 70 years (Durand et al., 2009) to coarser proxies further back in the past (Pfister, 1992; Casty et al., 2007).
- Backward trajectories of the socio-environmental context that may have affected avalanche activity and risk. These result from exploitation of historical archives and diachronic analysis of old photographs and maps: land use and land cover, population, possible construction of countermeasures, etc.

Specifically, the work involves three specific tasks detailed hereafter.

2.2.2 BUILDING A MODEL ACCOUNTING FOR NON-STATIONARITY

A hierarchical Bayesian probabilistic calibration method (Wickle et al., 1998) will be developed to make a depth-averaged avalanche flow model usable in a statistical framework with non-stationary input/output distributions for the data at hand. The method will build on the approach presented in Eckert et al. (2010d), but with the major difference that the underlying assumption of stationarity will be relaxed to possibly capture the evolution of avalanche activity drivers. To this end, the probabilistic models describing the avalanche flow inputs (release area and depth) and friction parameters of the rheological law will be made time-dependent according to robust parametric forms (different choices will be implemented and tested). Then, existing MCMC based calibration algorithms (Brooks, 1998; Gilks et al., 2001) will be adapted and their efficiency tested on synthetic data.

2.2.3 HIGH RETURN PERIOD AVALANCHES UNDER NON-STATIONARITY

The advantage of statistical-numerical models is to provide 1:1 relations between runout distance, return periods and the distribution of velocities or pressures associated to high-magnitude design events (e.g. 100-yr runout distance). The newly developed improved non-stationary version of the model will serve as a basis for expressing the temporal evolution of these parameters, as a first multivariate "risk" measure explicitly coping for non-stationarity in the snow and avalanche field.

2.2.4 RETRO-TRAJECTORIES OF AVALANCHE ACTIVITY AND RISK AND OF THEIR MAIN DRIVERS ON SELECTED HOTSPOTS

Ultimately, this framework will be used to simulate, on the targeted hot-spots, the full composite chronicle of past avalanche events, so as to reconstruct comprehensive backward trajectories of avalanche activity and, later, risk. To this end, inputs of each past even will be specified, in the developed statistical-numerical model, according to their climate and environmental context. We expect so to directly relate significant evolutions in avalanche activity to changes in snow and weather parameters and, hence, climate change. For instance, we should be able to highlight different behaviors of flow dynamics at the climax of the Little Ice Age (*LIA*) and for the warmest, most recent, decades, thus refining our knowledge on the influence of predominant control variables on snow rheology. Also, changes in land cover that may have impacted avalanche activity (such as forest cover extension and altitudinal coverage, or construction of defense structures) will be considered. We expect better understanding of the protective effect of forest cover, and how its interaction with avalanche activity results (or not) in an equilibrium state for the forest-avalanche system.

We will use no explicit modelling of the physics of avalanche triggers, but fit and use empirical relations between climate and environmental variables and release area and susceptibility. From the combination of these relations with the outputs of the non-stationary statistical-numerical model, changes in local magnitude-frequency relationships through time will be inferred. Ultimately, damage susceptibility relations such as those of Favier et al. (2015) will be included into the analysis to quantify how risk has evolved in the past as function of hazard changes combined with changes in number and nature of elements at risk (buildings, inhabitants, transportation corridors, etc.). These should provide new insights on how society and the damageable phenomena have interacted through time on the long range.

2.3 EXPECTED IMPACT

2.3.1 MAIN OUTCOMES

- Backward trajectories of avalanche activity and risk and of their main drivers on selected hotspots.
- Findings of much wider relevance regarding the rapid evolution of a sensitive mountain system whose social, exosystemic and climatic components strongly interact to generate risk.
- An innovative, unsteady, statistical-numerical modelling tool involving a depth averaged model fed with non-stationary input distributions. In addition to the direct outputs of the work, this modelling tool should allow, in the future, coupled with the increasingly available future snow-climate forecasts

(e.g. those of the Euro-cordex initiative [http://www.euro-cordex.net/] exploited in the framework of the project ADAMONT), refined impact studies to be conducted at the scale of at-risk sites. This may help anticipate future avalanche dynamics in a warmer climate, and, hence, design efficient adaptation strategies.

- A methodological contribution to the analysis, within a modelling framework, of long range chronicles originating from a variety of sources, and in which the discrimination of climatic and other effects is difficult. This should allow better understanding the advantages/limits of the different types of supports in terms of risk memory and its changes through time.
- All in all, a significant technical contribution to a wider interdisciplinary initiative involving historians, climatologists and ecologists in addition to statisticians and snow and avalanche specialists.

2.3.2 PUBLICATION STRATEGY

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

- Statistical developments regarding the use of composite data series within a probabilistic numerical flow code will be published in an applied statistics journal such as Journal of the Royal Statistical Society C or Envirometrics.
- The technical development of the non-stationary statistical-numerical model will appear in a journal from the application field such as The Cryosphere or Journal of Glaciology.
- Specific findings regarding the long range avalanche-climate relations may be published in Climatic Change, or Journal of Climate.
- Wider findings including relations to socio-environmental evolutions will be of interest for Science of the Total Environment or Global and Planetary Change.

3. Administrative and practical details

3.1: Rattachement

- Unité Erosion Torrentielle Neige et Avalanches (ETNA), Irstea Grenoble / Université Grenoble Alpes (UGA).
- Ecole Doctorale Terre Univers Environnement (ED 105, TUE) de la COMUE Grenoble Alpes.

3.2. Supervision and PhD committee:

- Supervision: Nicolas Eckert (Irstea ETNA).
- Co-supervision :
    - Samuel Morin (directeur du Centre d’étude de la Neige, CNRM, CNRS-Météo France).
- Other contributor to the PhD committee (at least one meeting per year during the PhD)
    - Anne-Marie Granet (Laboratoire de Recherche Historique en Rhône Alpes, Professeur d’histoire contemporaine).
    - Mohamed Naaim (Irstea).
    - Christophe Corona (Géolab).
    - Eric Parent (AgroParisTech,).
    - Christopher J. Keylock (University of Sheffield, United Kingdom).

3.3 Grant and salary conditions:

The PhD is fully funded. The successful applicant will receive a Post-doc stipend in line with that awarded by Irstea. Addition, financial support will be provided for conference attendances, etc.

3.4 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.

3.4 How to apply/contact:

Please e-mail nicolas.eckert@irstea.fr to first discuss the project.

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