PhD fellowship in extreme value statistics applied to cryospheric sciences**:**
Spatio-temporal patterns of extreme snowfall and snow depth in the French Alps using max-stable processes

Keywords:
Extreme climatic events, snowfall, snow depth, max-stable processes, spatial dependence, climate change, French Alps, OSUG complementarity and mutualisation

Abstract:
Heavy snow events are among the most severe natural hazards in mountainous countries. For extrapolating beyond the highest observed values in a spatial context Max Stable Processes (MSPs) is a natural however still very new framework. The objective of this PhD will be to implement and apply recent developments in MSPs theory to identify refined spatio-temporal patterns of extreme snowfall and snow depth in the French Alps. An exceptionally rich data set of many snow variables will be exploited, which may allow us to improve current knowledge about extreme snow events as a whole. First attempts of extreme snow modeling in the French and Swiss Alps have recently been made and this PhD will aim at going further. In particular, altitudinal effects will be taken into account in a finer way the influence of weather types on the spatio-temporal patterns of interest will be studied, and important hydrological and climatological hypotheses regarding extreme snow variables will be confirmed or infirmed. A particular attention will be paid towards the influence of topography and accumulation duration on directional effects, and towards the difference in spatial structure between extreme snowfall and snow depth. Furthermore, the explicit consideration of an unsteady framework will allow us to document or contest the assumption generally made of an increase of extreme snowfall/snow depth under ongoing climate change, especially at high altitude. Hence, this work is expected to produce results of high operational interest for, e.g., avalanche forecasting and winter water storage quantification, for instance by helping characterize the rarity of a severe storm not only locally but at its most relevant spatial scale through joint exceedence probabilities among a set of stations. The work will be done in very strong collaboration between three teams of the OSUG that will share and mutualize their data and skills through this work. Furthermore, resulting methodological developments and geophysical results may be relevant for various problems of the fields of interest of the OSUG community.

Detailed description of the proposed work:

Heavy snow events are among the most severe natural hazards in mountainous countries. Every year, winter storms can hinder mobility by disrupting rail, road and air traffic. Extreme snowfall can overload buildings and cause them to collapse, and can lead to flooding due to subsequent melting. Deep snow, combined with strong winds and unstable snowpack, contributes to the formation of avalanches, and can cause fatalities and economic loss due to property damage or reduced mobility. From a more “positive” point of view, extreme snow depths are relevant to quantify the total winter water storage in the snowpack.

For the quantitative analysis of extreme snowfall/snow depth, extrapolating beyond the highest observed values is often necessary. Extreme Value Theory (EVT) is then a theoretical framework to be used. It assesses that, for long enough records, block maxima (e.g. annual maxima) should be modeled by the so-called Generalized Extreme Value (GEV) distribution. In practice, things are however far from being that simple: spatial and altitudinal interpolation methods must be employed to make predictions outside from the measurement station locations, for instance at high elevations where available data are generally seldom. This explains why, in the engineering practice, “rule of thumbs” remain still heavily used while, e.g., evaluating accidental snow loads for structural design (Sadovsky et al., 2012).

To model spatial dependence in extreme values consistently with EVT, max-stable process (MSP) is an emerging approach generalizing EVT to the multivariate spatial case. Even if MSPs are based on the pioneering work of De Haan published as early as 1984, they have been applied in environmental sciences only very recently because of their mathematical complexity (Bel et al., 2007; Blanchet et al., 2009; Davison et al., 2012). This complexity has been decreased by Padoan et al. (2009) who proposed a practical inferential method by maximizing a composite likelihood. Furthermore, these authors showed how latitude, longitude, and altitude could be used as covariates to model rainfall data. Hence, the inferred extremal coefficient (the equivalent of the well-known variogram, but for extreme values) provides the dependence of extremes in space, while the spatially-varying GEV parameters allows predicting high quantiles at any point of the studied area.

Even more recently, Blanchet and Davison (2011) introduced anisotropy in spatial dependence within the same MSPs framework. Similarly, Gaume et al. (2013) successfully applied the three most classical MSPs (Smith, Schlather, and Brown-Resnick, Figure 1) together with spatially-varying GEV parameters (smoothing splines) to extreme snowfall in the French Alps. The authors were thus able to produce snowfall maps for different return periods and different accumulation durations all over the French Alps (Figure 2). This piece of information is very useful to understand the most severe avalanche activity periods (Eckert et al., 2010).

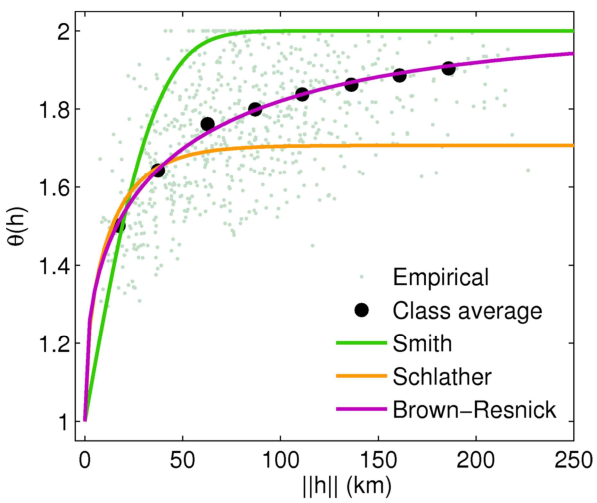

Figure 1: Extremal coefficient estimated for all pairs of stations as a function of the distance between the stations using likelihood maximization, from Gaume et al., WRR 2013

Gaume et al. (2013) highlighted an anisotropy in extremal dependence of snowfall in the French Alps, which is all the more important than the considered accumulation duration is short. Other studies also found anisotropy in various extreme hydrological variables, for exemple in extreme snow depth in the Swiss Alps in Blanchet and Davison (2011) or in U.S. precipitation in Padoan et al. (2009). In all case, it is related to orography and its main local direction. On the other hand, Blanchet and Davison (2011) and Gaume et al. (2013) obtained different results in terms of which MSP fits better the data. For Blanchet and Davison (2011)'s snow depth data, the spatially smooth Schlather MSP is selected, whereas it is rejected by snowfall data in France. This suggests a significant difference in the spatial structure of extreme snowfalls and of extreme snow depths at the ground level. It is likely to be related to the fact that spatial evolution of snow depth is much smoother than that of snowfalls due to cumulative effects involved in the formation of snow cover (successive snowfalls and snow metamorphism, whereas, in contrast, the asymptotic independence may be necessary for extreme snowfalls). However, to really validate this important hydrological conclusion, a deepened confrontation of extreme snow depths and snowfall data acquired over the same region is required, and it is therefore the first goal of the proposed work.

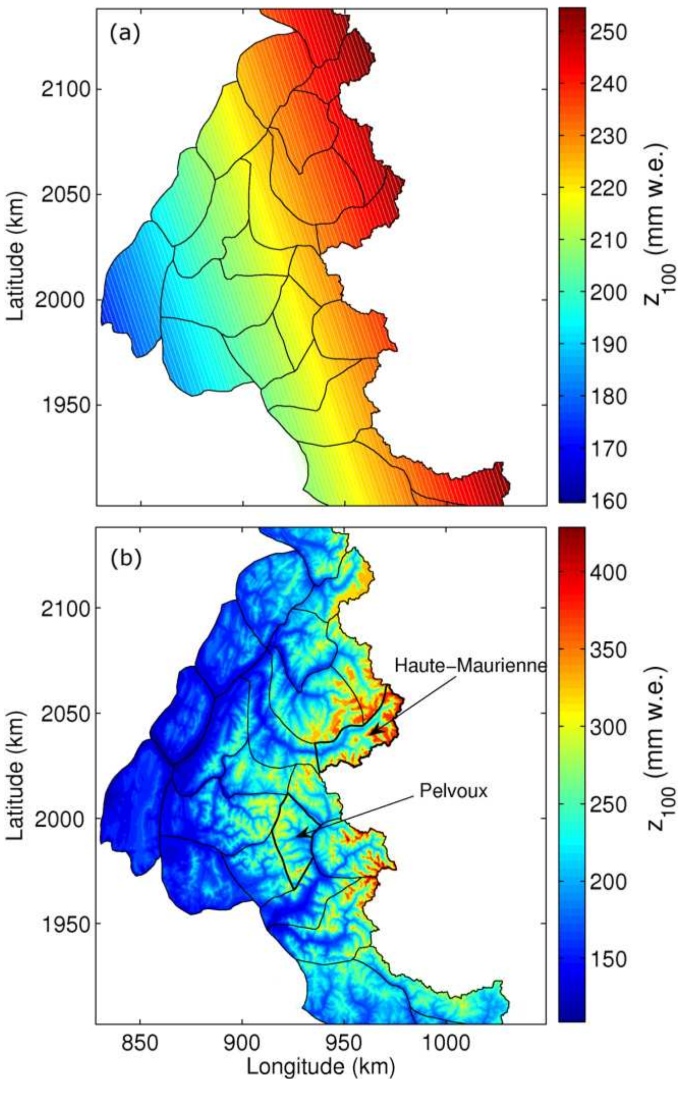

Figure 2: Maps of the 100 year quantile (a) at a fixed altitude of 2000 m and (b) projected on the relief using the cubic spline model from Gaume et al., WRR 2013

With regards to previous approaches in the same region (e.g. Weisse and Bois, 2001), Gaume et al (2103)'s. study is an important step forward from a methodological point of view because of the use of the MSP formalism. On the other hand, a limitation is that a relatively low amount of measurement stations has been used, mostly located in the valley bottoms. This was presumably enough for the main goal of the study, which was to produce rare snowfall maps usable in a coupled mechanical model to evaluate avalanche release depths for legal hazard zoning (Gaume et al., 2012), but it did not allow infer altitudinal effects in GEV parameters (an altitudinal correction that separates spatial and orographic effects has been made before the MSP fitting). A second objective of the proposed work is therefore to expand the analysis to the largest possible snowfall and snow depth data possible, mostly provided by Météo-France (e.g., Essery et al., in press). This includes conventional meteorological observation networks (real-time and climatological networks), dedicated snow observation networks (in particular snow observation network operated and managed by Météo-France in collaboration with ski resorts, and automated weather stations "Nivose") and renalayses of meteorological and snow conditions over mountain ranges (SAFRAN / Crocus simulations). Observations and numerical simulations span the period from 1958 to date with a significant increase in data quality and quantity in the early 1980s. Extensions to snow water equivalent (SWE) are possible using the methodological framework developed for snow depth data. Hence, by separating snow/rain events at various altitudes and getting rid of the density effects, we hope to be able to obtain robust altitudinal trends in GEV parameters (assessed by cross validation). The clear distinction from latitude/longitude effects will allow comparing the resulting "extremal gradients" with the few results of this kind available in other countries.

Another limitation of all previously mentioned MSPs approach is that they did not consider the current context of a changing climate which makes the assumption of stationary conditions generating extreme snowfall events discussible. Indeed, IPCC's (2012) report predicts rise in extreme climate events, and it is generally admitted that high elevations are among the most sensitive areas (Beniston et al., 1997). However, even if a possible increase of extreme snowfall/snow depth has indeed been often postulated on the basis of simulation results (Lopez Moreno et al., 2009; 2012), Marty and Blanchet (2012) have shown that it is not easy to assess it in a proper extreme value analysis of snow variables. It is therefore a third goal of the project to do all the analyses within a spatio-temporal framework by making the GEV margin of the MSP depend on time explicitly. First answers to the question of possible recent changes of extreme snow variables in the French Alps are therefore expected, so as to possibly relate and confront them to time trends in annually averaged climatic variables over the same region (Durand et al., 2009). A better understanding of the trends in avalanche activity (Eckert et al., 2013) and their altitudinal control (Lavigne et al., 2012) which have been recently documented is also anticipated.

Finally, to partially bridge the gap between statistical climatology and weather forecast, it will be investigated whether spatio-temporal dependence patterns in extreme snowfall vary according to the main atmospheric fluxes that drive them (snow depth is then less relevant because it accumulates through the winter). To do so, a relevant weather type classification (e.g. Garavaglia et al., 2010) will be used to partition extreme snowfall occurence, and we hope to be able to express the overall pattern obtained without considering the weather type classification as a weighted mean of patterns corresponding to each weather type. At our knowledge, such a study has never been performed anywhere in the world.

To sum it up, the main expected outcomes of the proposed work is the identification of refined spatio-temporal pattern of extreme snowfall and snow depth in the French Alps. In opposition to previous approaches over the same region, an exceptionally rich data set of various snow variables will be exploited, which may allow take better into account altitudinal effects, perform cross validations at various elevations, study the influence of weather types of the spatio-temporal patterns of interest, and confirm (or infirm) important hypotheses of rather general hydrological and climatological relevance regarding extreme snow variables: the influence of topography and accumulation duration on directional effects, and the difference in spatial structure of snowfall/snow depths. Furthermore, the explicit consideration of an unsteady framework will allow document or contest the assumption generally made of an increase of extreme snowfall/snow depth under ongoing climate change, especially at high altitude. Hence, this work is expected to produce results of high operational interest for, e.g., avalanche forecasting, for instance by helping characterize the rarity of a severe storm not only locally but at its most relevant spatial scale through joint exceedence probabilities among a set of stations.

From a methodological point of view, the very recently developed formalism of MSPs will be heavily used to infer spatial and altitudinal dependence patterns in extremes. In addition to manipulating existing statistical packages and routines, additional developments will be necessary. They may concern the practical implementation of the new MSPs that may soon become available from research in theoretical probabilities and may be of interest for our data as well as the selection of the most adapted MSP and of the associated covariates in the GEV margins among a set of possible choices, a problem far from being closed. To do so, the PhD fellow will benefit from a supervision team having contributed to the most up-to-date developments in this field (see below).

The work will be supervised by Dr. Nicolas Eckert (IRSTEA Grenoble, http://www.irstea.fr/en/eckert), Dr. Juliette Blanchet (CNRS/LTHE Grenoble, http://www.lthe.fr/PagePerso/blanchet/) and Dr. Samuel Morin (CNRM/GAME Snow study centre Grenoble, http://www.cnrm.meteo.fr/spip.php?article250). Although administratively based in Irstea, the PhD fellow will be a full member of the three concerned Irstea, LTHE and CEN teams, which includes access to team facilities (seminar, etc.) and data in the different labs. Hence, the work will be done in very strong collaboration between three teams of the *Observatoire des Science de l'Univers de Grenoble* (OSUG) that will share and mutualize their data and skills through this work. This may lead to methodological developments, knowledge capitalization and geophysical results important for numerous problems of the fields of interest of the OSUG community, for instance the analysis of extremes of various simulation outcomes.

Required qualification

Applicants should have a master in statistics, hydrology, snow science or related topics. Past research work in extreme value analysis and/or snow-cryospheric statistical modelling would be appreciated. Applicants should be fluent in oral and written English. Knowledge of a programming language (e.g., R, Matlab) is required. This job is offered with no restriction on age, sex or nationality, in accordance to French law.

Salary conditions and financial support:

The successful applicant will receive a PhD stipend in line with that awarded by Irstea, which currently amounts to ~€1,852 per month (including taxes). In addition, financial support will be provided to fund travel (conferences) and publication costs.

How to apply:

Complete the template online at the TUE doctoral school: http://www.obs.ujf-grenoble.fr/ecdoc/sujets-de-these.php. Feel also free to e-mail us to discuss the project at nicolas.eckert@irstea.fr, juliette.blanchet@ujf-grenoble.fr and samuel.morin@meteo.fr.

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