Evaluating extreme snow avalanches in long term forecasting

N. Eckert
IRSTEA Grenoble, UR ETNA, Saint Martin d'Hères, France

Contributions:
E. Parent, L. Bel, O. Guin, AgroParisTech, Equipe MORSE-UMR 518 , Paris, France
M. Naaim, D. Richard, IRSTEA Grenoble, Saint Martin d'Hères, France

Groupe « extrêmes »
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A few words about snow avalanches

Complex snow flows

Different possible flow regimes

Constraining factors for avalanche release and propagation:
topography and nivo-meteorology

Main variables:
snowfalls and cumulated snow depths, temperature fluctuations, snow drift, etc.

Dense flow avalanche impacting a deflecting structure

Powder snow avalanche

Avalanche risk in the (French) Alpine space

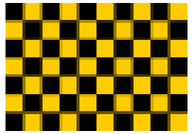
Snow avalanches are a significant hazard in the (French) Alps:
- Between November and may
- In about 600 townships in France
- Characterised by its suddenness (no evacuation after release) and brutality (destructions)

Concerns :
- people rather than infrastructures: 30 deaths/year in France
- skiers, back-country skiers and ski resorts
- roads and communication networks
- buildings and inhabitants (lack of space)

House destroyed by a powder snow avalanche, French Alps

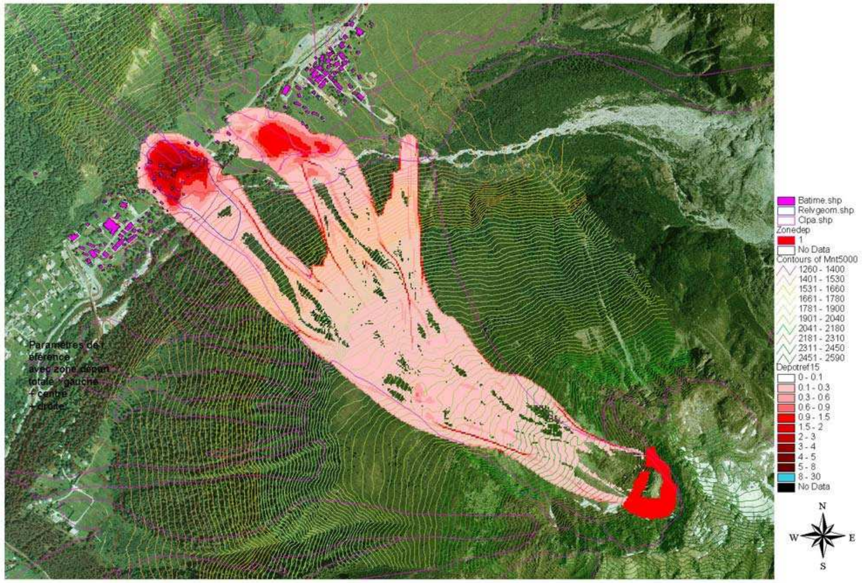
Avalanche risk mitigation

Long term land use planning ≠ avalanche forecasting



Snow and weather data and snow cover model (real time data assimilation) + « risk » level computation

Hazard mapping and zoning



Avalanche numerical simulation for hazard mapping

Construction of countermeasures

Passive defense structure

Reference hazards in the snow and avalanche field

Legal thresholds for land use planning based on return periods (like hydrology): 100 years in France, 30-300 years in Swiss, up to 1,000 years in Iceland…

Multivariate definition : runout distance (travelled distance) / impact pressure

Historically, high return period avalanches were evaluated roughly by « experts » using local data, experience, etc…

1998/99 catastrophic avalanche winter:

Montroc (Haute Savoie, France), 9 February 1999, building moved and destroyed

→ Need for more systematised and statistically consistant methods to evaluate high return period avalanches

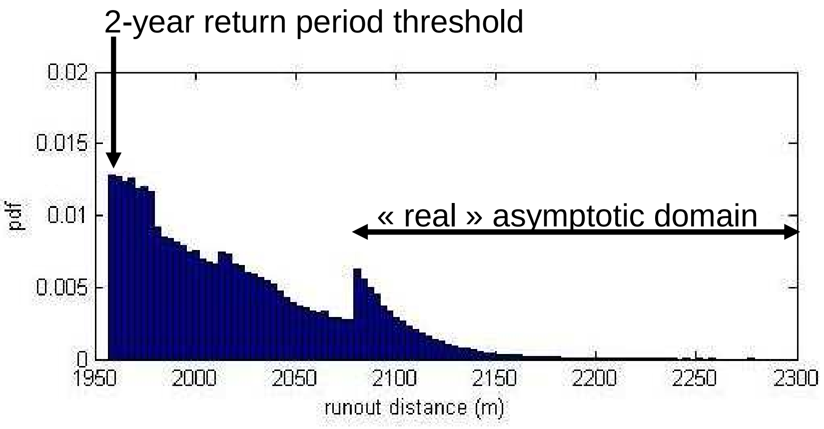
Are we using EVT for snow avalanches?

Runout distance is the most critical variable

Univariate EVT-like approaches : GEV/GPD fits of samples of runout distances (McClung and Lied, 1986; Keylock, 2005), with possible use of covariates (regression)…

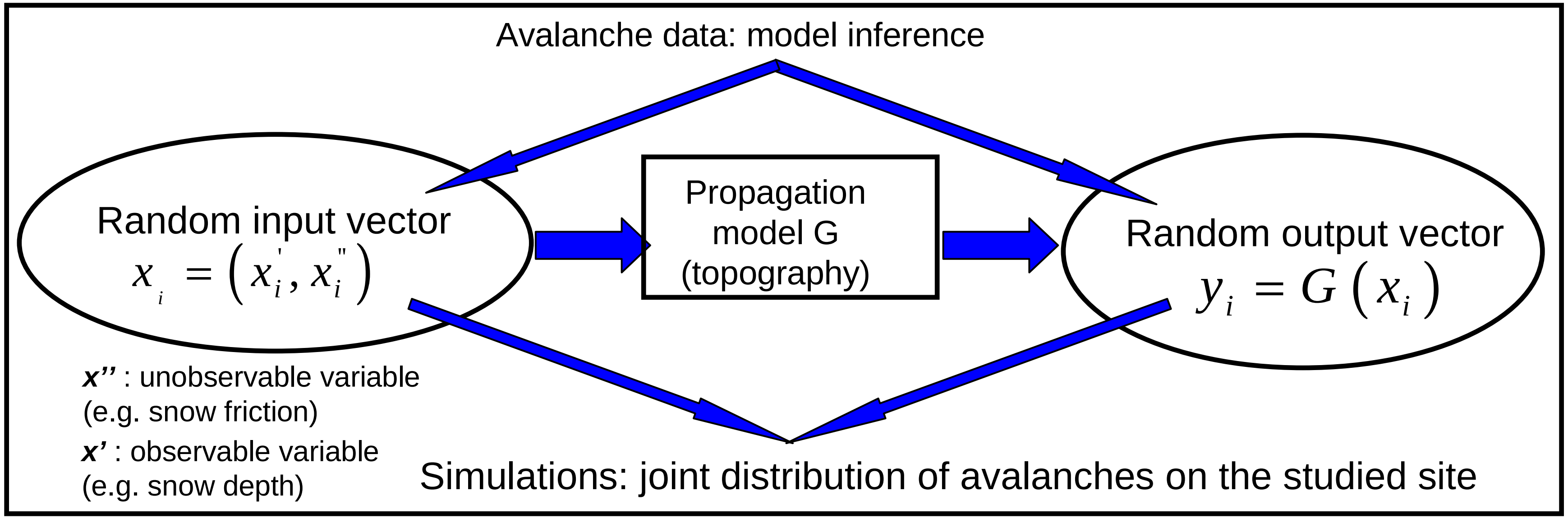
Problems:
- Data collection protocol not clear (block maximas – threshold exceedences)
- Short local series: are asymptotic conditions fulfilled?
- Can data from different sites be pooled together after standardization?

For instance, very strong dependency on topography
- concave runout zone: light tail
- convex runout zone: heavy tail
- irregular runout zone: mixture of tails



Other variables must be quantified (velocity, pressure, flow depth, etc.) and few data available: multivariate EVT not used, except for snowfalls in a spatial context (Blanchet et al., 2009)

The alternative: statistical-numerical (physical) modelling



Pioneer work: Barbolini and Keylock (2002), Ancey et al. (2003)

Modelling issues:
- Deterministic propagation model
- Stochastic modelling of the correlated random input vector

Technical issues:
- inference with a complex model
- simulation: physical reliability like framework (computationally intensive)

Numerical modelling of avalanche flows

Numerous models available:
- Different types of avalanches: dry/wet snow, dense and/or powder snow avalanche
- Different modelling approaches (sliding block, fluid mechanics, granular mechanics)
- Snow rheology (friction law) remains heavily discussed

A reasonable compromise between precision of the description of the flow and computation time for the *G* transfer function:

$$\begin{cases} \dfrac{\partial(hv)}{\partial t} + \dfrac{\partial}{\partial x}(\alpha_{sv} h v^2 + k_{sv} g \dfrac{h^2}{2}) = h\left[g \sin\phi - \left(\mu g \cos\phi + \dfrac{g}{\xi h} v^2 \right) \right] \\ \dfrac{\partial h}{\partial t} + \dfrac{\partial (hv)}{\partial x} = 0 \end{cases}$$

fluid description of the avalanche flow (depth averaged) and Voellmy friction law: Naaim et al., 2004

<u>Additional assumption:</u>

μ related to path roughness : parameter (one per site)

ξ related to snow quality (humidity, grain size) : latent variable (one per avalanche)

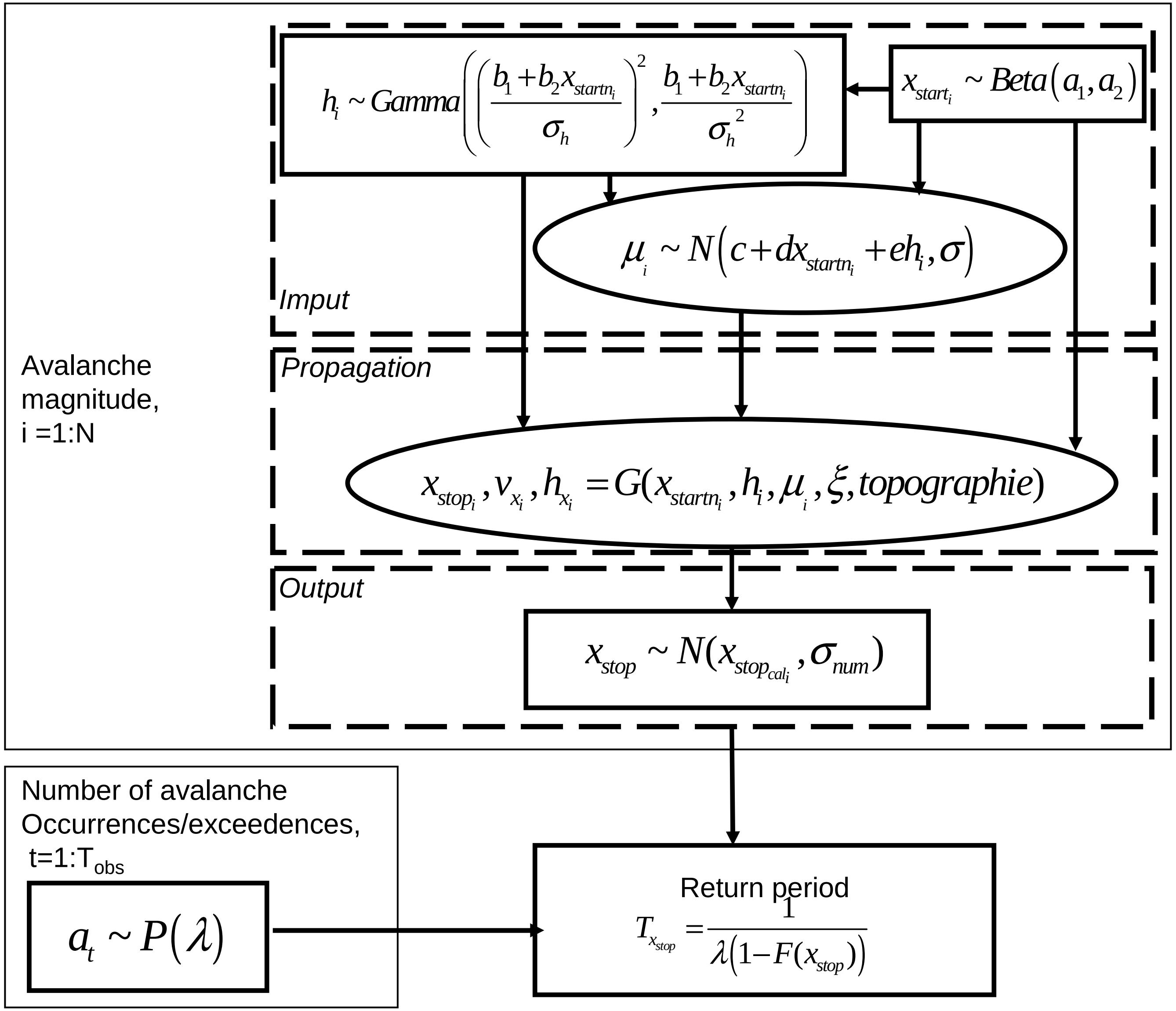
Building a statistical-numerical multivariate POT model

Joint modelling of the observable and latent input variables using conditional modelling: release position and depth, and latent friction coefficient

Transfer function: avalanche propagation

Gaussian differences between observed and simulated runout distances

Independent modelling of avalanche magnitude and number of occurrences/exceedences: "pseudo POT model" (Eckert et al., 2010)

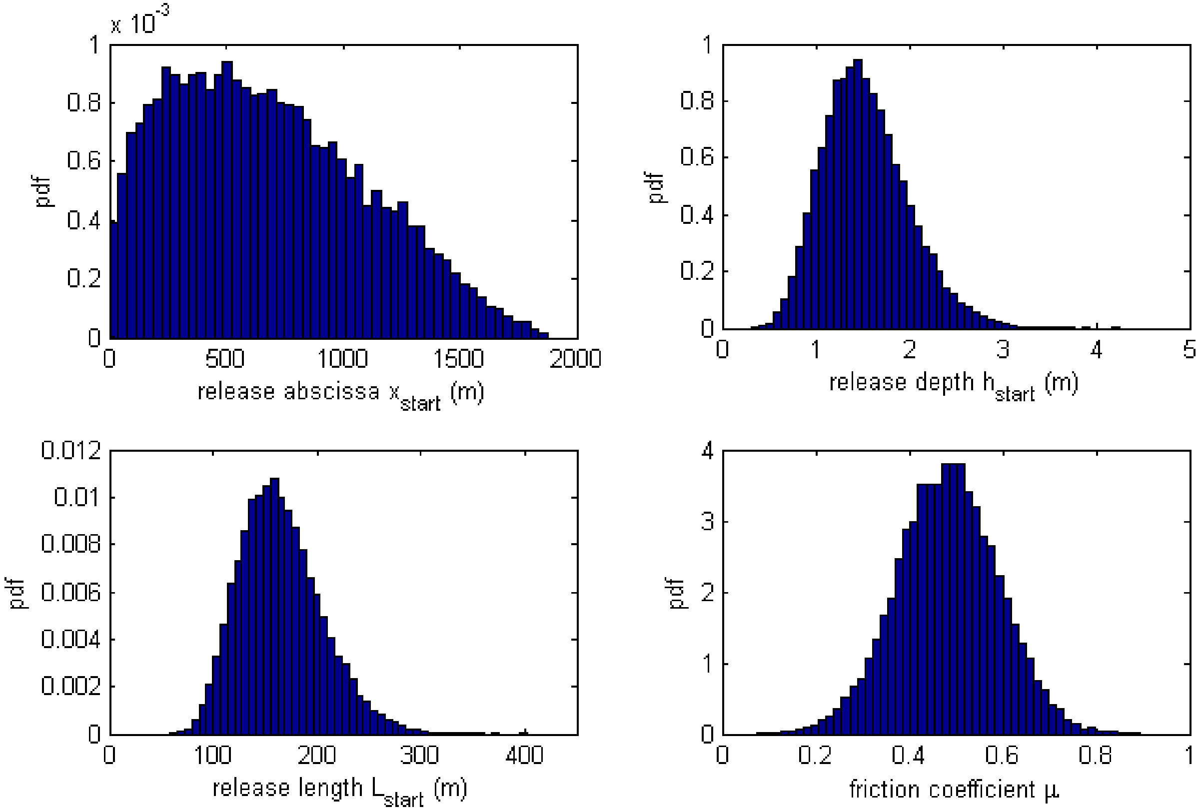


Return period for the runout distance

Simulation: joint distribution of model variables

$$p\left(x_{stop}, v, h... \middle| \hat{\theta}_M\right) = \int p\left(x_{start} \middle| \hat{a}_1, \hat{a}_2\right) \times p\left(h_{start} \middle| \hat{b}_1, \hat{b}_2, \hat{\sigma}_h, x_{start}\right) \times p\left(x_{stop} \middle| x_{start}, h_{start}, \mu, \hat{\xi}\right) \times d\mu$$

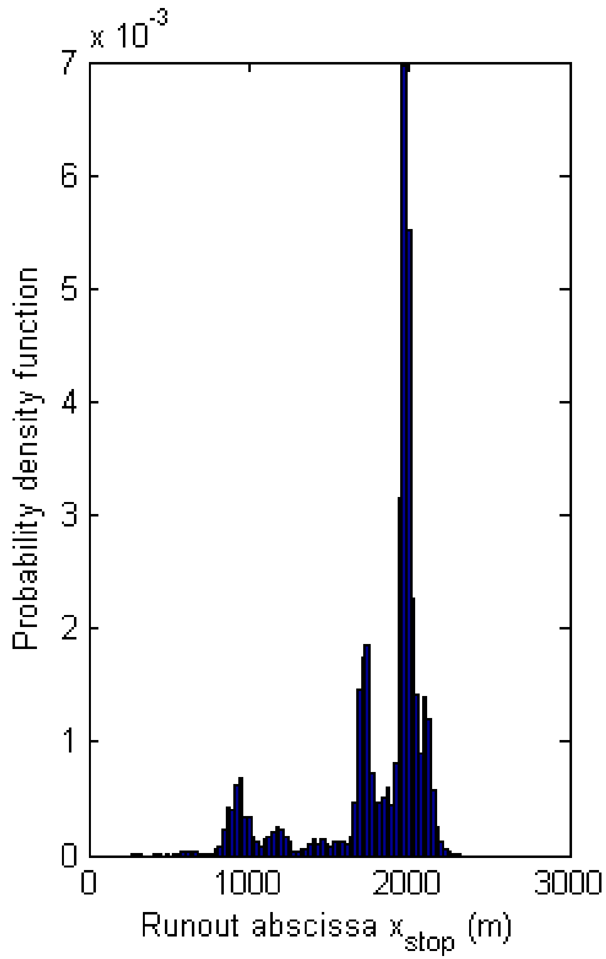
Monte Carlo simulations:
- standard Monte Carlo scheme: slow $\sqrt{n}$ convergence speed
- accelerated (directional or others) Monte Carlo methods: faster convergence
- integration over hidden variables

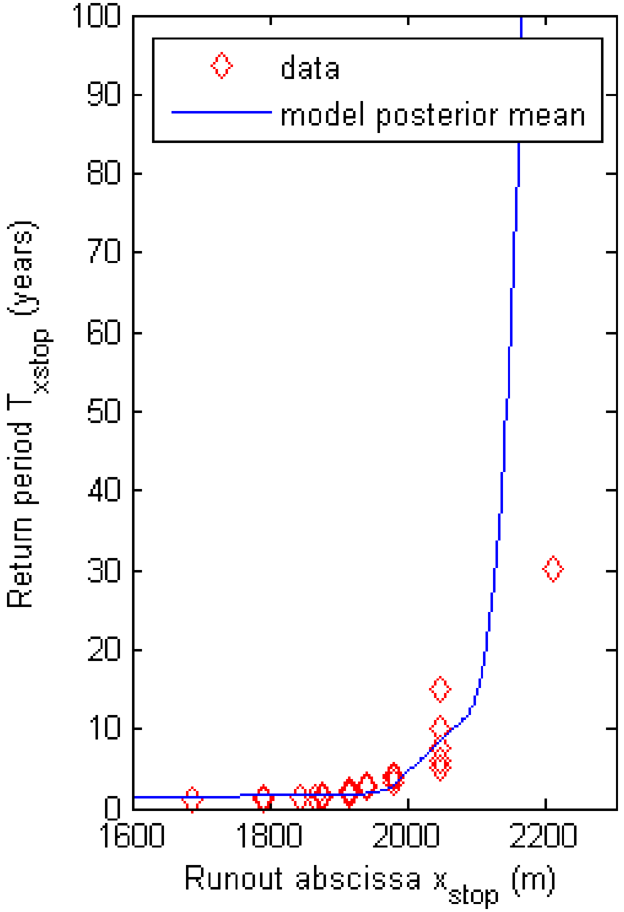


Joint distribution of the variables of the non fully explicit avalanche magnitude model

Runout distance and return periods

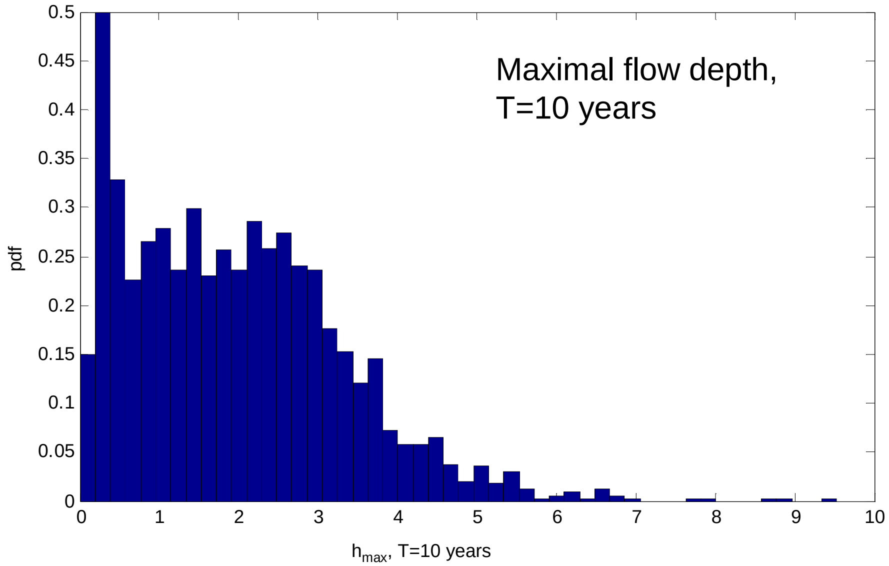
Return period for each abscissa combining:
- a point estimate of the mean avalanche occurrence/threshold exceedence number $\hat{\lambda}$
- the estimated runout distance cdf $\hat{F}(x_{stop})$

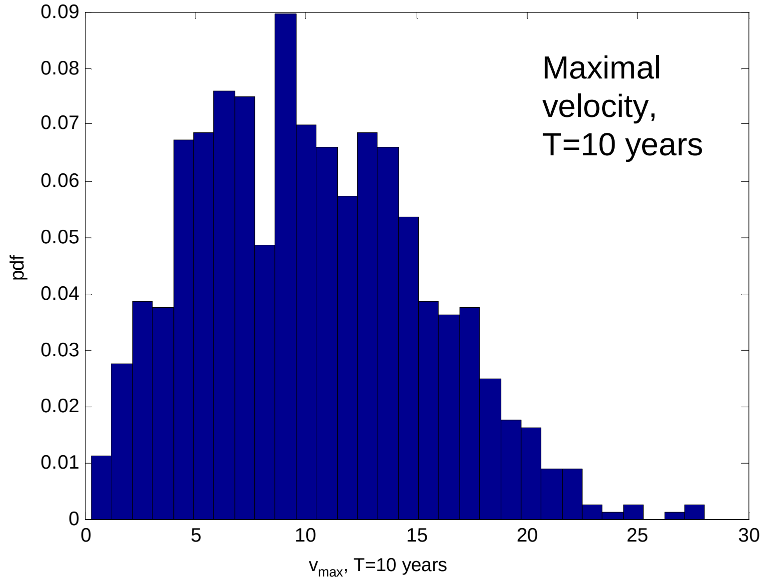


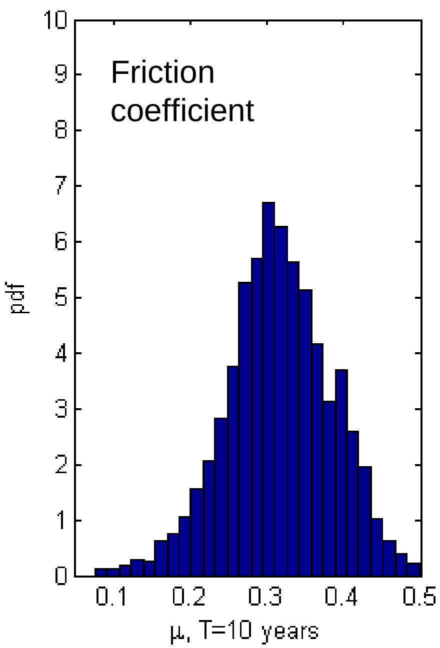


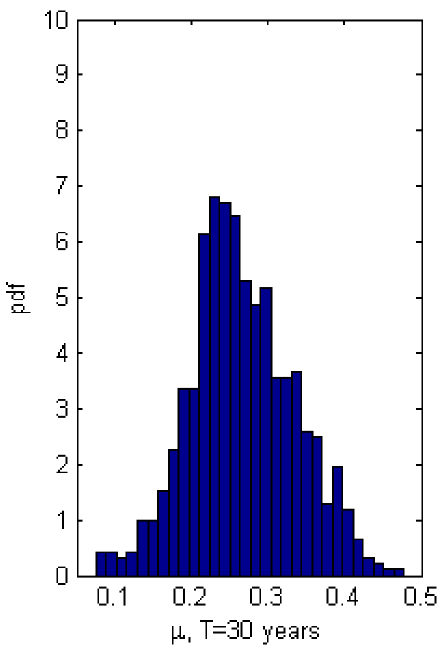
$$T_{x_{stop}} = \frac{1}{\hat{\lambda} \times \left(1 - \hat{F}(x_{stop})\right)}$$

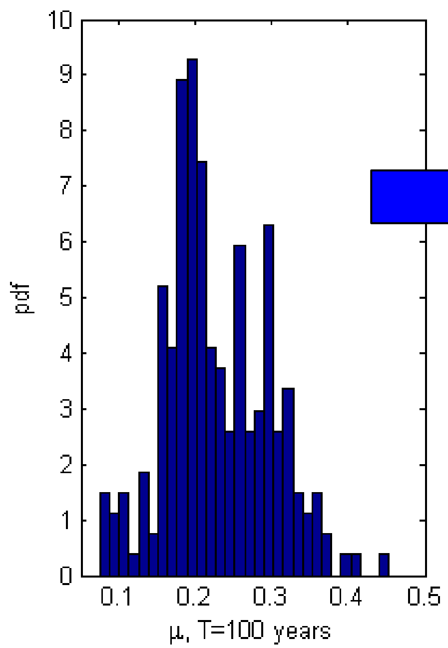
Joint distribution P(v,h,μ.. I $x_{stop} > x_{stopT}$)











Hazard mapping and zoning, Structural and functional design of defense structures

Flow properties and impact pressure

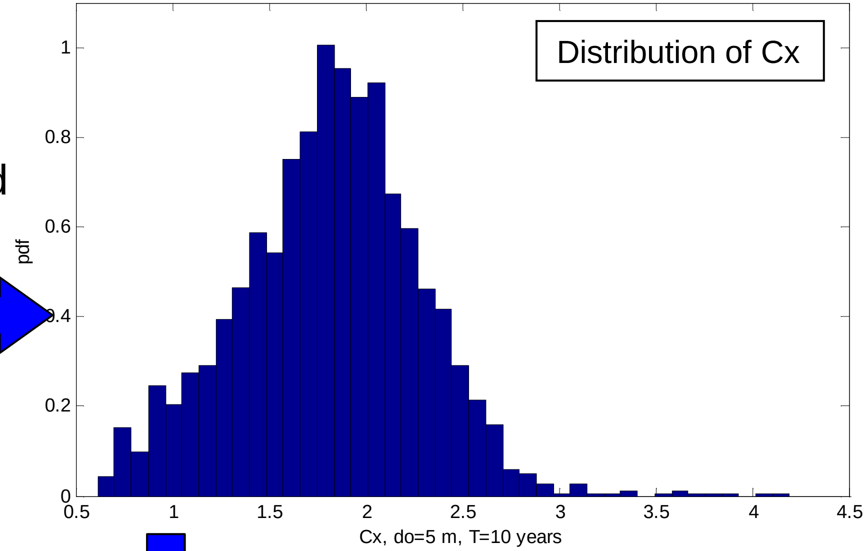
$$\mathrm{Pr} = Cx \frac{1}{2} \rho_N v^2$$

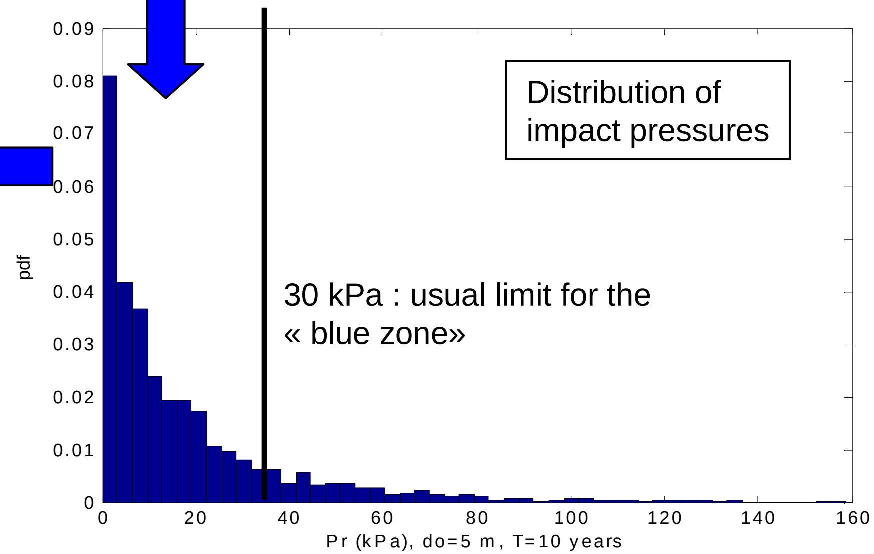
: A constant Cx (drag coefficient) is not appropriate for snow

Theoretical formulation for a complex fluid
Naaim et al. (2008) :

$$Re = \frac{25}{4} \frac{Fr^2}{\cos\phi \sin\phi} \left(\frac{d_o}{h} \right)^2$$

$$Cx = 196.02 \left(Re \right)^{1/5} \left(\log_{10} \left(Re \right) + 3 \right)^{-3.37}$$





- Structural design of defense structures
- « Full » reference scenarios

Bayesian inference for the magnitude model

Bayes' theorem for parameters and latent variables:

$$p\left(\theta_M, \mu, x_{stop_{cal}} \middle| data, \sigma_{num}\right)$$
$$\propto p(\theta_M)\times\prod_{i=1}^{N}\left(l\left(x_{start_i}, h_i, x_{stop_i} \middle| \theta_M, \mu_i, x_{stop_{cal_i}}, \sigma_{num}\right)\times p\left(\mu_i, x_{stop_{cal_i}} \middle| \theta_M, x_{start_i}, h_i, x_{stop_i}, \sigma_{num}\right)\right)$$

Prior — Likelihood — Distribution of latent variables

Conditional specification of the model:

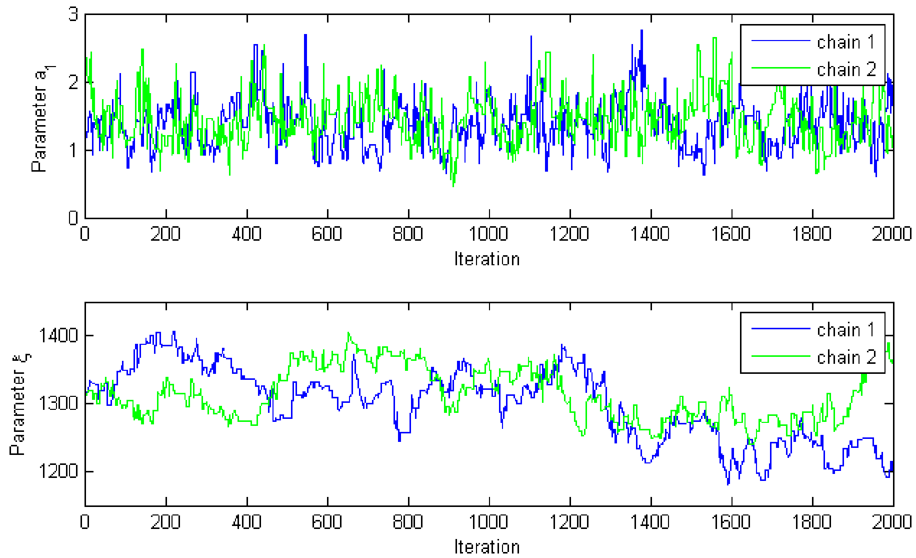
$$l\left(x_{start_i}, h_i, x_{stop_i} \middle| \theta_M, \mu_i, x_{stop_{cal_i}}, \sigma_{num}\right) = l\left(x_{start_i} \middle| a_1, a_2\right)\times l\left(h_i \middle| b_1, b_2, \sigma_h, x_{start_i}\right)\times l\left(x_{stop_i} \middle| \sigma_{num}, x_{stop_{cal_i}}\right)$$

Deterministic propagation:

$$p\left(\mu_i, x_{stop_{cal_i}} \middle| \theta_M, x_{start_i}, h_i, x_{stop_i}, \sigma_{num}\right) = p\left(\mu_i \middle| c, d, e, \sigma, x_{start_i}, h_i\right)\times\delta\left(G(x_{start_i}, h_i, \mu_i, \xi)\right)$$

MCMC simulations:
- Gibbs and sequential MH within Gibbs
- Tuned by adapting jump strength
- Converge diagnosis: Gelman and Rubin test

Computationally intensive…



MCMC sequence for two model parameters with low and high autocorrelation, respectively

Generic principle of MCMC algorithms

Vector of unknown quantities: $w = (\mu_i, x_{stop_i}, a_1, a_2, b_1, b_2, \sigma_h, c, d, e, \sigma, \xi)$

Iterations of an ergodic Markov chain

$w^{(0)} \quad w^{(1)} \quad \ldots \quad w^{(b)} \quad w^{(b+1)} \quad \ldots \quad w^{(p-1)} \quad w^{(p)}$

Initialisation and burn in

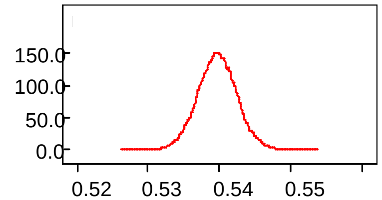
Ergodic behaviour (convergence)

Metropolis Hastings (MH) algorithm

2 steps for each iteration :

$w^{(l-1)} \rightarrow w^{*}$ **Candidate (jump function)**

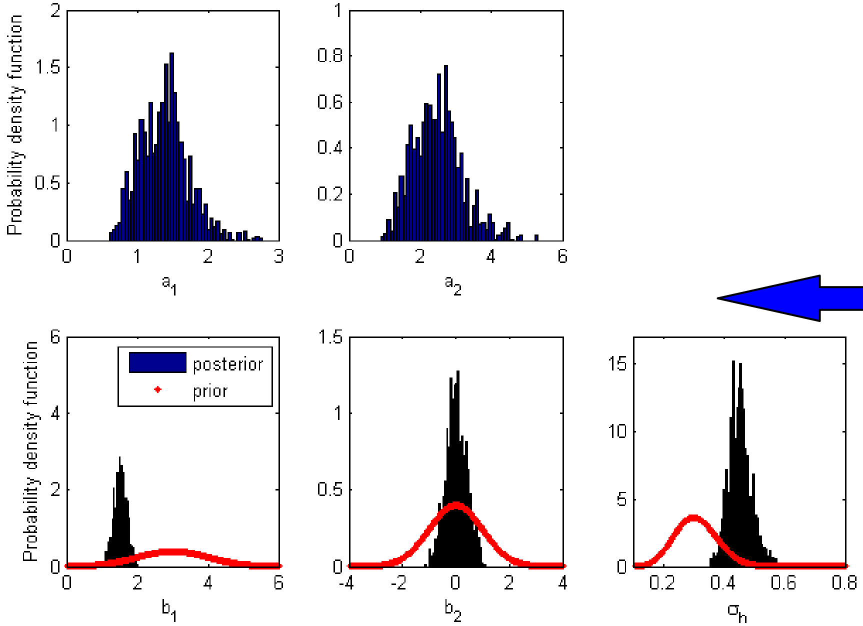
Probabilistic acceptance/rejection rule $\rightarrow w^{(l)}$

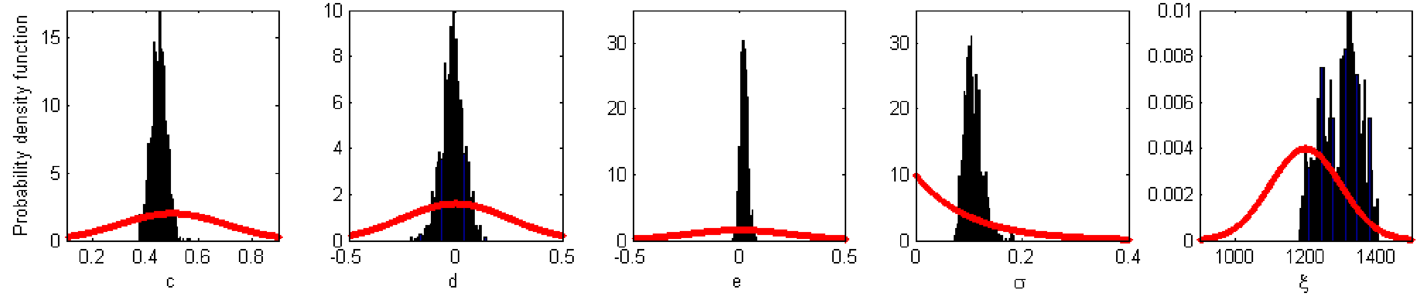


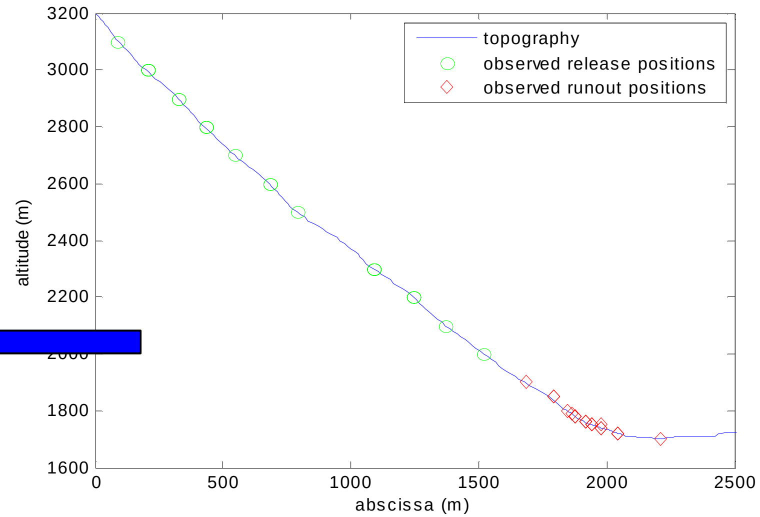
« Target » joint posterior distribution

- Very simple in theory
- Subtle in practice (choice of the jump functions is case-study dependent)

Posterior distributions of magnitude model parameters





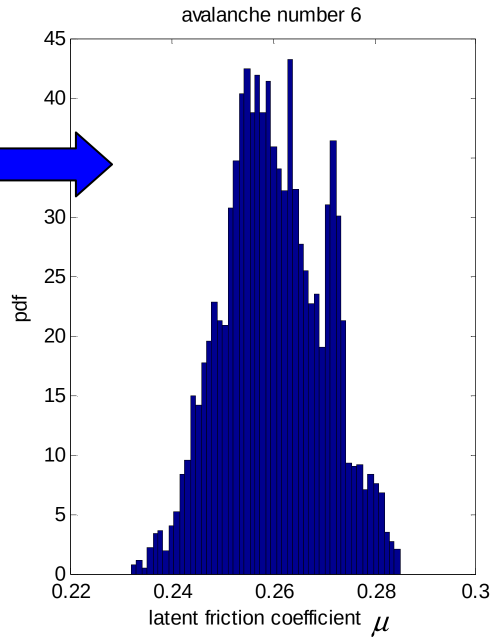


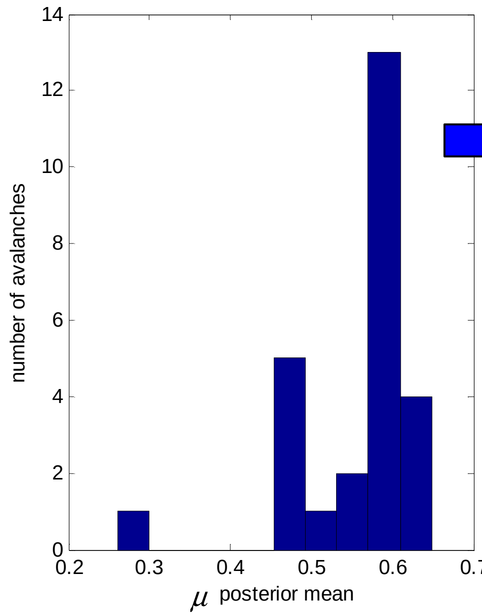
Case study: Bessans township, France, path 13

- Friction coefficient ξ and parameters describing the variability of the input variables
- Computation time : 2 weeks

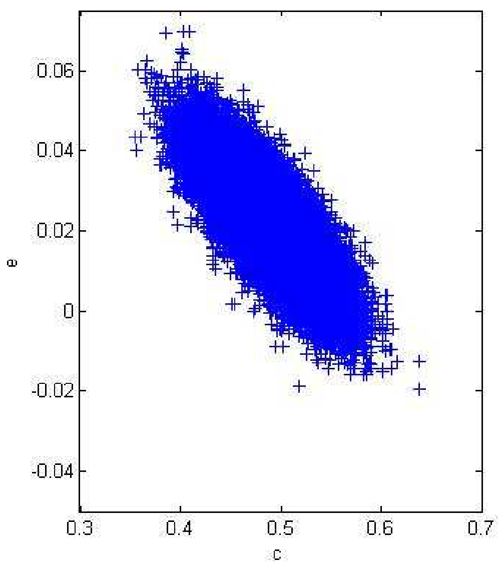
Latent variables and posterior correlation

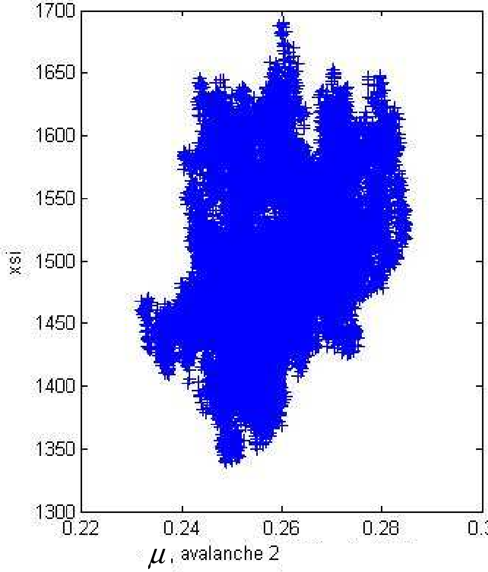
Posterior distribution of the frictions coefficients corresponding to each avalanche





Point estimates





inter parameter correlations

Compensations, especially between the two friction coefficients

Bayesian prediction of high runout distance percentiles

- Predicted percentile/return period averaged over posterior pdf (Eckert et al., 2008):

$$p\left(x_{stop_q}\,|data\right)=\int F^{-1}_{x_{stop}|\theta_M}\left(q/100\right)\times p\left(\theta_M\,|data\right)\times d\theta_M$$

$$p\left(x_{stop_T}\,|data\right)=\int F^{-1}_{x_{stop}|\theta_M}\left(1-\frac{1}{\lambda T}\right)\times p\left(\theta_M\,|data\right)\times p\left(\lambda\,|data\right)\times d\theta_M\times d\lambda$$

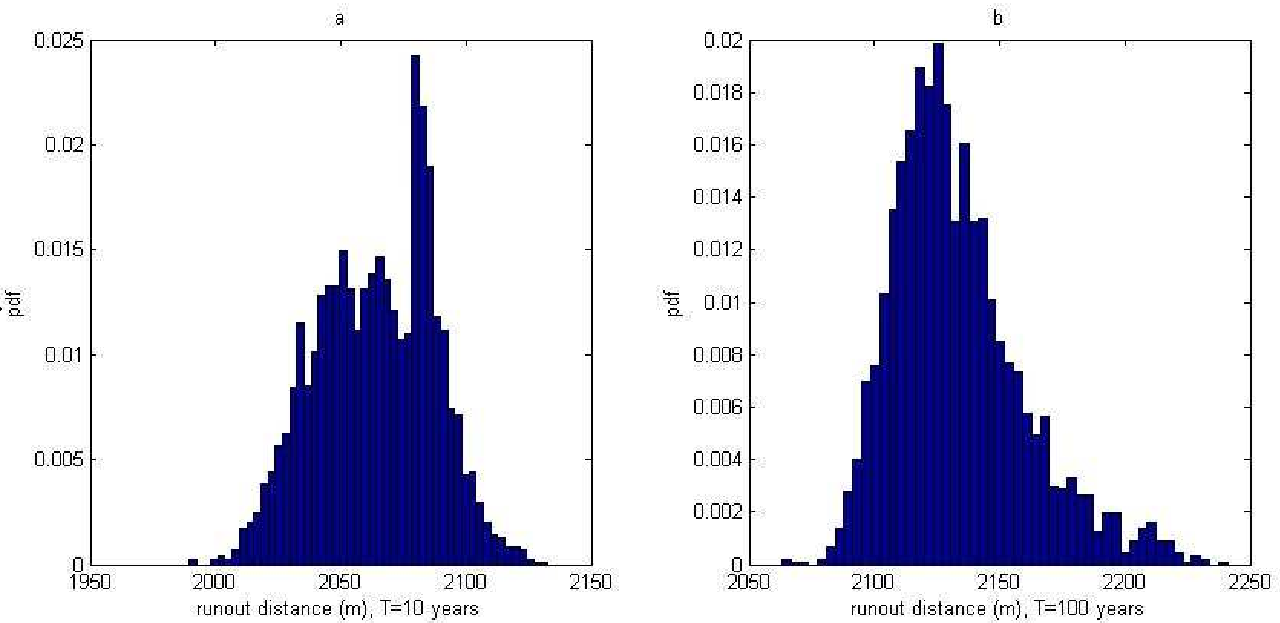
- Fair representation of uncertainty associated to the limited data quantity

- Alternative method to delta-like methods under the classical paradigm

- Computationally intensive!

Abscissas corresponding to return periods of a) 10 years and b) 100 years.

Mean, variance and skewness increase with return period: critical for hazard evaluation



Back to EVT : Avantages and limitations

+ Knowledge integration (data, prior, physical model, statistical model…)

+ Model's output distribution can be as complex as necessary, depending on topography

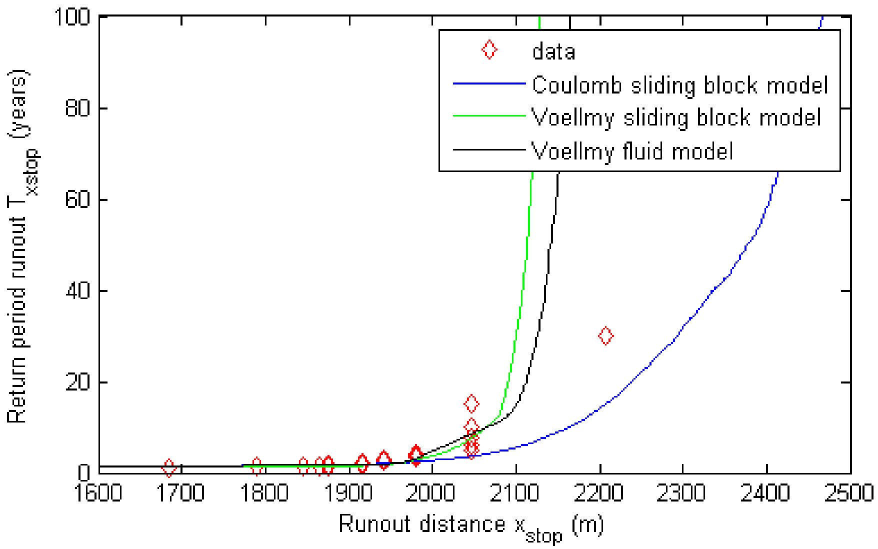
+ Multivariate approach with dependence structure given by physical constraints: respects mass and momentum conservation and snow flow rules

- Calibration on « mean » events!
  - Standard EVT says there is few link with extremes, except the attraction domain…
  - "Where" is asymptotics for snow avalanches?

- Variables of interest (runout distances, velocities…) are not modelled by extreme value distributions: "empirical" rather than limit model
  - Extrapolation ?
  - Asymptotic properties ?

Validation of model predictions?

- No unique limit model available: sensitivity analyses with competing “empirical” statistical-dynamical models (propagation model, stochastic description of the inputs/outputs…)



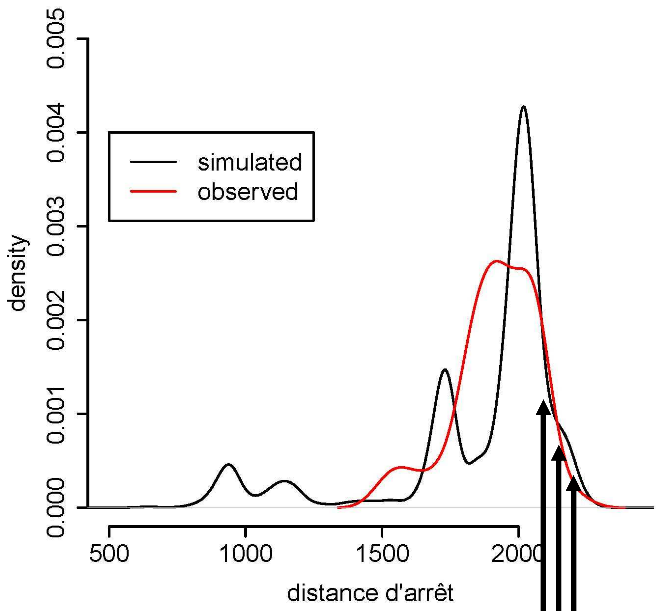
Sensitivity to the propagation model: magnitude-frequency relationship provided by three statistical-dynamical models with the same information:

- Alternatively, use other “fossil” data when available for validation (dendrogeomorphology): work in progress

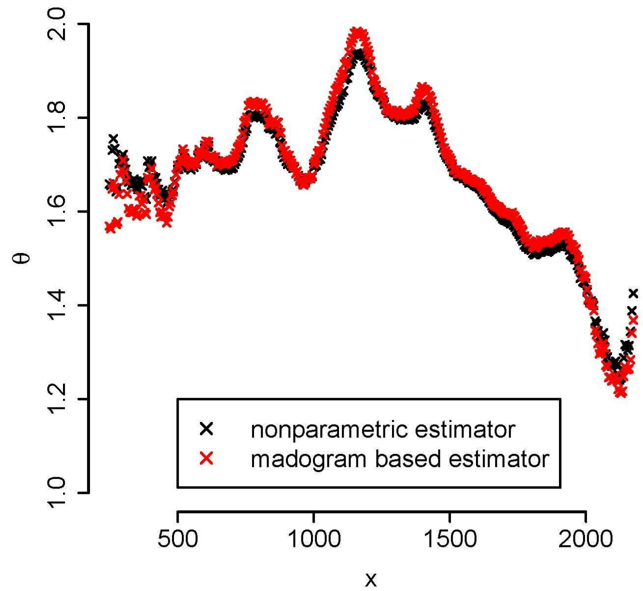
Asymptotic properties of avalanches simulations

Attraction domains and asymptotic dependence (Coles et al., 1999) of simulated avalanches:
- possible comparison with observations for runout distances
- exploratory for other variables (useful in practice)
- work in progress

$$P\left(X_1^* \le u, X_2^* \le u\right) = P(X_1^* \le u)^{\theta}$$



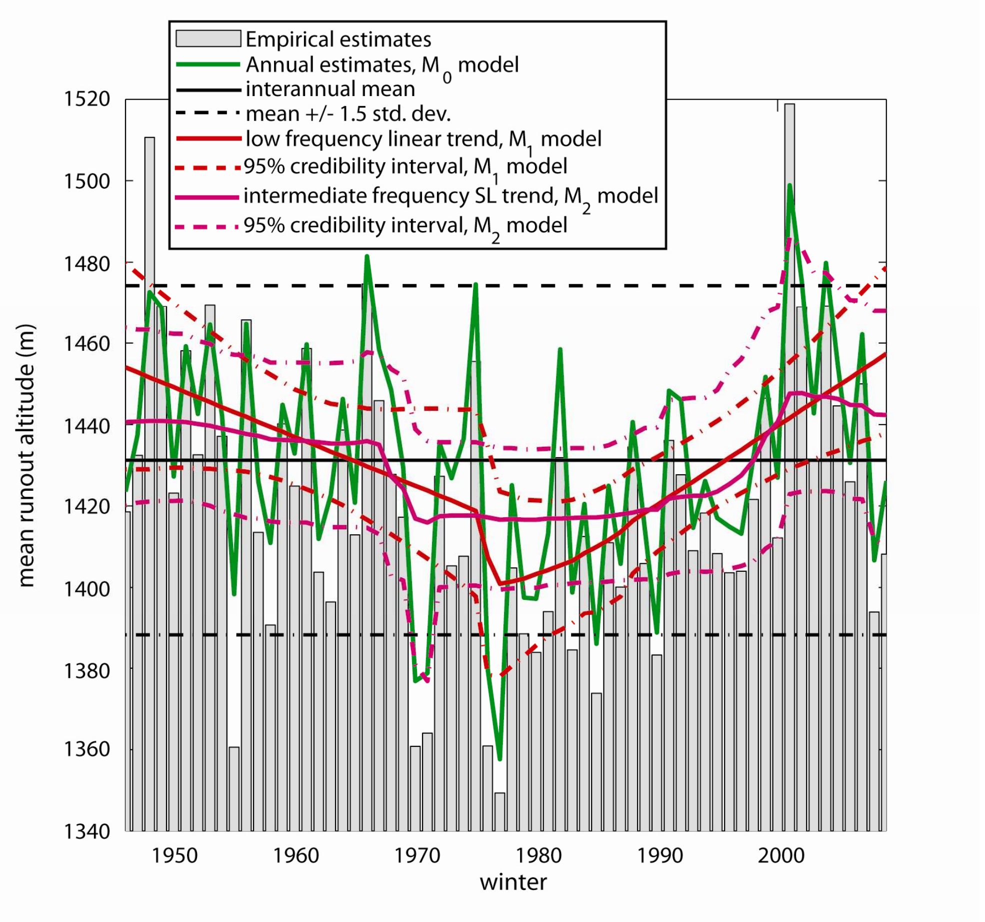
GPD fits on simulated/observed runout distances: similar shape parameters for different thresholds



Asymptotic dependence between runout distance exceedences and maximal velocities as a function of the position in the path: Strong dependence in the runout zone (critical)

Response to climate change and stationarity

- Everything has been done under stationarity assumptions, which does not correspond to trend analyses…
- Good correlation of trends with recent climate change
- Expansion of the framework to unsteady snow and weather forcing conditions remains to be done



Mean runout altitude on a mean path from the French Alps derived from Eckert et al., 2010

Conclusion

- **Extreme value problems exist in snow avalanches**
  - Direct use of EVT cannot solve “everything”
  - Robust physics may help

- **A useful framework for avalanche engineering in practice :**
  - Computation of multivariate reference hazards
  - Simple algorithm for model calibration
  - Uncertainty quantification
  - Can be included in a (Bayesian) decisional framework

- **Raises interesting “theoretical” questions**
  - Coherence between the physical model and EVT
  - Computational issues in inference and simulation (emulation…)
  - Extreme value prediction under (space-time) unstationarity with limited data

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  - For your attention
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References…

Ancey, C., Gervasoni, C., Meunier, M. (2004). Computing extreme avalanches. Cold Regions Science and Technology. 39. pp 161-184.

Barbolini, M., Keylock, C.J. (2002). A new method for avalanche hazard mapping using a combination of statistical and deterministic models. Natural Hazards and Earth System Sciences, 2. pp 239-245.

Blanchet, J., Marty, C., Lehning, M. (2009). Extreme value statistics of snowfall in the Swiss Alpine region. Water Resources Research, Vol. 45, W05424, doi:10.1029/2009WR007916.

Coles, S., Heffernan, J, Tawn, J. (1999). Dependence measures for extreme value analyses. Extremes 2:4. pp 339-365.

Eckert, N., Parent, E., Naaim, M., Richard, D. (2008) Bayesian stochastic modelling for avalanche predetermination: from a general system framework to return period computations. Stochastic Environmental Research and Risk Assessment. 22. pp 185-206.

Eckert, N., Naaim, M., Parent, E. (2010). Long-term avalanche hazard assessment with a Bayesian depth-averaged propagation model. Journal of Glaciology. Vol. 56, N°198. pp 5 63-586.

Eckert, N., Baya, H., Deschâtres, M. (2010). Assessing the response of snow avalanche runout altitudes to climate fluctuations using hierarchical modeling: application to 61 winters of data in France. Journal of Climate. 23. pp 3157-3180.

Keylock, C. J. (2005). An alternative form for the statistical distribution of extreme avalanche runout distances. Cold Regions Science and Technology. 42. pp 185-193.

McClung, D., Lied, K. (1987). Statistical and geometrical definition of snow-avalanche runout. Cold Regions Science and Technology 13. pp 107-119.

Naaim, M., Naaim-Bouvet, F., Faug, T., Bouchet, A. (2004). Dense snow avalanche modelling: flow, erosion, deposition and obstacle effects. Cold Regions Science and Technology. 39. pp 193-204.

Naaim, M., Faug, T., Thibert, E., Eckert, N., Chambon, G., Naaim, F. (2008). Snow avalanche pressure on obstacles. Proceedings of the International Snow Science Workshop. Whistler. Canada. September 21st-28th 2008.