18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Assessing the impact of climate change on snow avalanche activity in France over the last 60 winters using hierarchical Bayesian spatio-temporal change point models

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Abstract: Snow avalanches are mainly ruled by temperature fluctuations, heavy precipitations and wind regimes, so that climate change is likely to modify the frequency and magnitude of both ordinary and extreme events. However, reference scenarios and return periods for avalanche hazard management are always computed in the engineering practiced under the assumption of a stationary process. On a more phenomenological point of view, contrary to other phenomena such as tropical storms, snow avalanches are very rarely used as proxy indicators that point out signals of climate change.

This study focuses on avalanche occurrences and runout altitudes in France over the last six decades. For both variables, a hierarchical spatio-temporal modelling framework is proposed to quantify the interannual fluctuations possibly resulting from climate change. First, the regional annual component is isolated from the total variability using a nonlinear analysis of variance. Second, the latent structured time trend is distinguished from the random noise with different time series shifting level sub-models. The hierarchical structure obtained takes into account the uncertainty related to the estimation of the annual component for the quantification of the time trend. Bayesian inference is performed using Markov Chain Monte Carlo simulations.

Avalanche occurrences are studied in the northern French Alps. No systematic modifications in occurrence regime could be found over the last 60 years. This suggests that climate change has recently had little impact on the avalanching rhythm in France. Significant temporal patterns have though occurred. They consist in complex combination of abrupt changes and pseudo-periodic cycles of approximately 15 years.

Avalanche runout altitudes are studied in the whole French territory. A change in runout altitude regime has occurred in France around 1976. Between 1946 and 1976, a decrease of 55 m has affected the mean runout altitude, but the probability of a high magnitude event has remained constant. After the change point, the mean runout altitude has regained its initial state, whereas the probability of a high magnitude avalanche has been divided by two. A retreat of avalanche is therefore engaged in France since nearly 30 years. This especially concerns high magnitude events, since the return period associated with an avalanche reaching its minimal altitude on a mean path has increased from 20 to 40 years over the last 30 years.

Avalanche occurrences and runout altitudes are therefore differently influenced by changes in constraining climatic factors, so that the interest of a joint temporal modelling of the two phenomena would be limited. One possible explanation is that dry snow avalanches are progressively replaced by wet snow avalanches because of climate worming, thus keeping constant the number of events, but reducing their magnitude by modifying snow rheology. To confirm this statement, further research is needed to compare and explicitly correlate the obtained annual effects with climatic data such as precipitation and temperature series. This will allow improving our knowledge on climate change in the alpine space and its consequence on avalanche hazard.

Keywords : *Snow Avalanches, Climate Change, Hierarchical Bayesian Modelling, Change Point Models, Avalanche occurrences, Runout Altitudes.*

1. INTRODUCTION

Climate change is likely to modify the frequency and magnitude of both ordinary and extreme snow avalanches. Papers dealing with this question generally analyze the evolution of the snow cover rather than the changes in avalanche activity. Snow cover under a given climatic scenario has though been modeled, with the main result being that an increase of the proportion of wet snow avalanches compared to the dry snow ones seems realistic (Martin et al., 2001). Analyses of real avalanche data generally focus on the last few decades. Schneebeli et al. (1997) have for instance seen no change in the number of catastrophic avalanches around Davos, Switzerland, during the 20th century. Keylock (2003) has pointed out correlations between avalanche activity in Iceland and the North Atlantic Oscillation.

From the statistical point of view, extracting a climatic signal from an avalanche series is fairly complex. First, avalanche activity is characterized by several variables (occurrence, runout distance, snow volume, etc.) and one or several of them has to be chosen. Second, the different effects that explain the observed data have to be separated in order to extract the common annual component that is related to the large-scale climatic fluctuations. Third, the isolated latent climatic component has to be modeled to extract the structured part of the interannual fluctuations. Step 2 can be seen as an analysis of variance (ANOVA), with one of the considered factors being the annual component. Depending on the variable studied, a transformation may be necessary so as to relate the observation to a Gaussian and generally Markovian random field. The third step is a classical time series analysis that can put to use a large variety of models, depending of the temporal patterns investigated, for instance memory effects, monotonic trends, or change points for the mean, the variance and/or the extreme values of the series considered. It must be emphasized that steps two and three cannot be separated because the uncertainty related to the estimation of the temporal term must be taken into account for the estimation of the time trend. Steps two and three should therefore be implemented in a hierarchical framework, so as to isolate the temporal component and explicitly model it within the same statistical treatment (Clark and Gelfand, 2006). The Bayesian approach is appropriate, providing simulation-based MCMC algorithms for inference (Brooks, 1998).

In two recent papers, a hierarchical Bayesian framework has been used to study the fluctuations in France of avalanche occurrences (Eckert et al., 2009a) and runout altitudes (Eckert et al., 2009b). These two variables quantify frequency and magnitude of damageable events and are therefore crucial for hazard assessment. For both of them, the best time series model has been selected among a relatively large class using the DIC criterion. In this paper, the results provided in each case by the best model are summarized. Then, the annual and structured effects are analyzed, looking for possible correlations between avalanche occurrences and runout distances fluctuations over the last 60 years.

2. FRENCH AVALANCHE DATA

The "Enquête Permanente sur les Avalanches – EPA" is a chronicle describing the avalanche events on about 3,800 determined paths in the French Alps and Pyrenees. Its aim is not to register all the events on all the French avalanche paths, but to be as exhaustive as possible on the paths considered. Avalanche counts are registered, along with several qualitative and quantitative information. The field data are collected by forest rangers and are stored by the Cemagref in a database. In this paper, all runout altitudes acquired since 1946 are considered, whereas avalanche occurrences are only modeled in the northern French Alps, though the most active region at the country scale. Since World War II, observation errors are reasonable in the database, which justifies the choice of a time period $T_{obs} = 60$ years for both data sets. Note that here a year is a winter, the year 2000 corresponding, for example, to the winter of 2000/2001. Aberrant values were detected using simple statistical tests. This decreases the sample size, but provides more reliable estimates. For runout altitudes and avalanche occurrences, respectively 19,960 and 21,682 events were kept into the analysis. The high number of runout altitudes discarded is explained by multiple error sources (imperfect localization of certain paths in the past, changes in maps available for observation, etc.).

3. FLUCTATIONS OF AVALANCHE OCCURENCES IN THE NORTHERN FRENCH ALPS

3.1. Hierarchical shifting level model

For avalanche occurrences, a spatio-temporal approach is conduced at the scale of the township. The number of avalanches in the township j during the winter t is noted a_{jt}. M is the total number of townships in the region studied and T_{obs} the length of the observation period. A non homogenous Poisson observation model is postulated, which is classical for rare discrete events (Figure 1). The parameters $\lambda_{jt}, j \in [1, M], t \in [1, T_{obs}]$ quantify the spatio-temporal variability of avalanche activity. To detect spatio-temporal patterns, the annual observations are compared to a mean behavior e_j expected in each township from the local topographical and nivological characteristics under the assumption of space and time stationarity. Moreover, a hierarchical model is used to share information between the different townships. The log-relative risks are therefore decomposed into different effects: a spatially structured term u_j, a locally unstructured term v_j, a temporal term g_t and an interaction term h_{jt}.

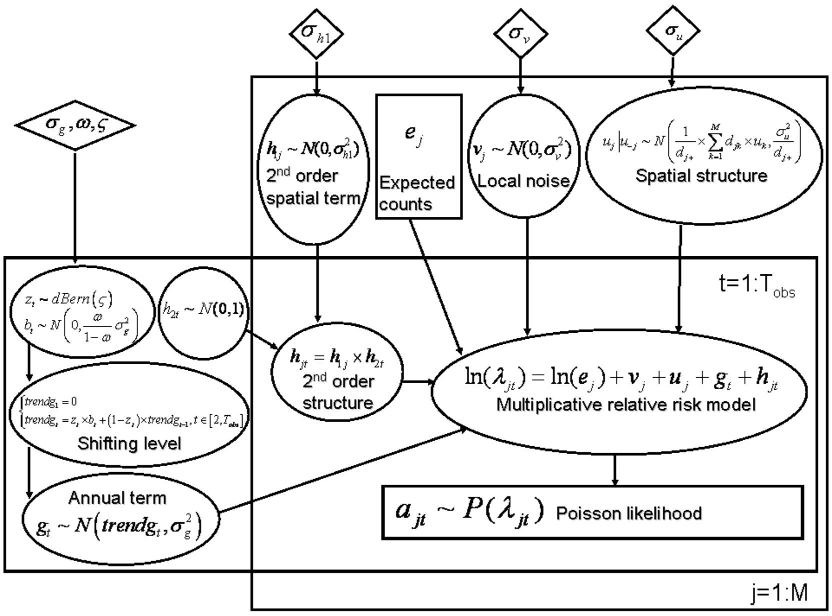

Figure 1. Model for avalanche occurrences. The circled nodes represent stochastic latent variables and the diamonds represent the overall parameters, while the rectangles indicate observed values.

The spatial term is based on a distance matrix d_{jk}. The local value u_j is smoothed by all the components $u_{k \neq j} = u_{-j}$ with a level of smoothing depending on an overall spatial variance σ_u^2 and on the inverse of the total distance d_{j+} between the township considered and all the other townships. The term v_j takes into account a strong local excess or default in the local relative risk using a white noise with variance σ_v^2. The interaction term models the possible nonlinear effects that may affect each township each year. Its decomposition into second-order spatial h_{1j} (with variance σ_{h1}^2) and temporal h_{2t} random noises allows reducing the number of parameters. g_t models annual variations in the relative risks, which similarly affect all the townships of the region considered. The time series of g_t is therefore directly related to the climatic fluctuations and is presumably a good indicator of the impact of climate change on avalanche activity. It is here modeled as a combination of a temporal white noise with variance σ_g^2 and a shifting level model (Salas et Boes, 1980). The simplest way to express the shifting level model is to consider an auxiliary discrete random variable z_t following the Bernoulli distribution. Its single parameter ς quantifies the annual probability of a level shift. If z_t=1, a new regime b_t is reached. b_t is distributed as a white noise, with a variance $\sigma_{shift}^2 = \frac{\omega}{1-\omega}\sigma_g^2$ quantifying the inter-regime variability. The parameter ω quantifies the balance between the inter-level variability σ_{shift}^2 and the random noise σ_g^2. The structured trend $trendg_t$ corresponds to the succession of the different regimes. It's posterior distribution is estimated by computing its value at each iteration of the MCMC sequence.

3.2. Application

Box plots give practical and concise representations of the marginal posterior distribution of each annual component g_t (Figure 2, top). The lowest value is obtained for winter 1963/1964, for which only five avalanches were registered. On the contrary, the maximal value is obtained for winter 1994/1995, which was a harsh winter during which the maximal annual number of avalanches was recorded in the EPA database. Winter 1998/1999, the last catastrophic winter in the European Alps, also shows a very high value for g_t, though not the highest. This is explained by the fact that here all events are considered, and not only the most catastrophic ones. The ratio $r_{temp} = \frac{\sigma_g^2}{VAR[u] + \sigma_v^2 + \sigma_g^2 + \sigma_h^2}$ quantifies the contribution of the interannual variability to the total variability of avalanche occurrences. Its estimate is 0.17. A little less than 20% of the variability of avalanche occurrences is therefore explained by the interannual fluctuations, which is relatively small, but not insignificant. This low value stems principally from the large spatial variability of avalanche occurrences in the northern French Alps.

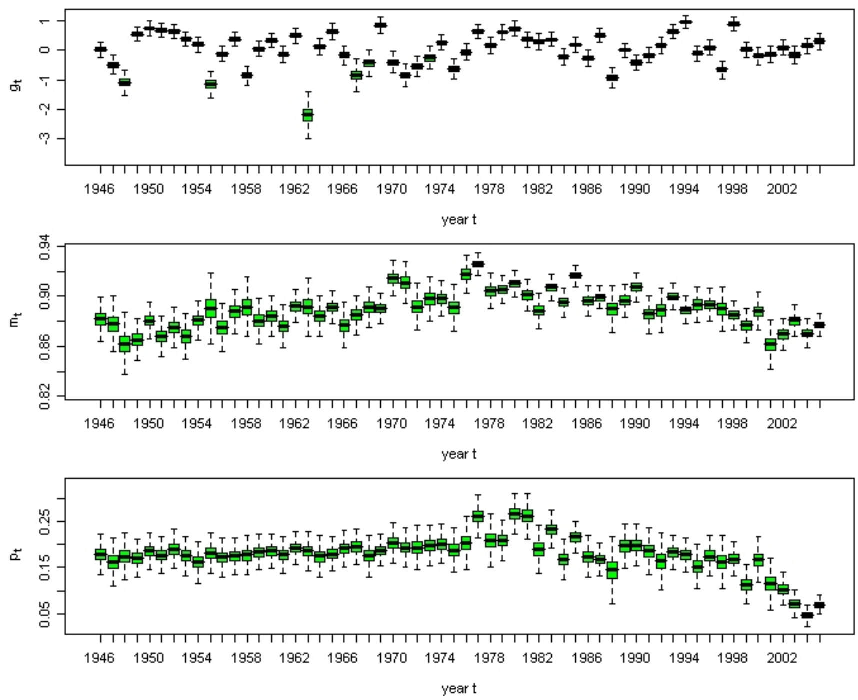

Figure 2. Box plots of the annual components in avalanche occurrences, mean runout altitude and probability of reaching the valley floor in France.

No monotonic trend such as a constant increase or decrease over the period studied is visible on Figure 2 (top). This indicates that there is for the moment no irreversible change in avalanche activity in the northern French Alps. On the other hand a combination of different time structures exists. First, memory effects can be suspected, with many sequences of consecutive years showing close values, for example between 1949 and 1954. Second, cyclic variations seem to occur, with a succession of four cycles of around 15 years, with maxima around 1951, 1965, 1980 and 1995. Finally, abrupt variations also exist, with very low values directly following very high values, for example, between 1962 and 1963 or between 1987 and 1988. The interannual trend $trendg_t$ provided by the shifting level model consists therefore in a complex combination of pseudo-periodic cycles and abrupt changes (Figure 3, top). The ratio $\frac{\mathrm{Var}(trendg_t)}{\mathrm{Var}(trendg_t) + \sigma_g^2}$ indicate that the structured variability explains 42% of the interannual variability, and therefore approximately 5% of the total variability of avalanche occurrences. However, since w =0.46, the strength of the level shift σ_{shift} is only on the same order of magnitude as σ_g. As a consequence, the relatively good model fit obtained is rather the result of model's flexibility than of the presence in the data of successive significantly different regimes.

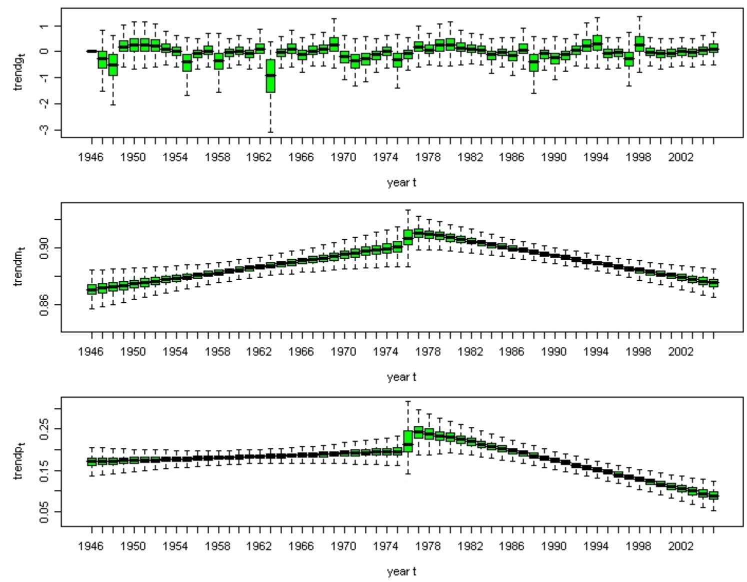

Figure 3. Box plots of the structured annual components separated from random noise in avalanche occurrences, mean runout altitude and probability of reaching the valley floor in France.

4. FLUCTUATIONS OF AVALANCHE RUNOUT ALTITUDES IN FRANCE

4.1. Change point model

For avalanche runout altitudes z_{ijt}, a simpler modelling approach is employed. A normalization by the altitude of the valley floor z_{min_j} is used to compare data from one path to another. This defines a Runout Altitude Index (RAI), with $N(j)$ the number of avalanches recorded on the path $j \in [1, M]$. *M* is here the total number of paths under survey (Figure 4). Interannual fluctuations can be summarized by the mean annual index $m_t = E_t\left[RAI_{ijt}\right]$ and the annual probability of high-magnitude avalanches $p_t = P\left(RAI_{ijt} = 1\right)$.

Since a significant number of avalanches reach the valley floor, the annual distribution of the RAI is modeled by a mixture of two distributions. RAI_{ijt1} is a discrete random number taking the value 1 if the avalanche i reaches its possible minimal altitude, with an annual probability p_t. RAI_{ijt2} is a continuous random number whose annual distribution is possibly skewed and can therefore be modeled by a Beta distribution with an annual parameter pair (α_t, β_t). The annual mean m_t is easily obtained from the model's parameters. As a consequence, the triplet (p_t, m_t, β_t) fully characterizes the RAI annual distribution. To capture the systematic variations of mean- and high-magnitude avalanche runout distances, the m_t 's and the p_t 's are modeled as nonexchangeable latent variables with a model simple, but one flexible enough to capture a monotonic trend and various types of changes in mean and variance. τ is the year of a possible change point separating two periods of different runout regimes. Before and after the change point, both the m_t 's and the p_t 's are broken down into random noises and structured linear trends. The random noises, with variances $\left(\sigma^2_{m1}, \sigma^2_{m2}, \sigma^2_{p1}, \sigma^2_{p2}\right)$, model the unstructured interannual fluctuations before and after the change point for mean and high magnitude runout altitudes respectively. The structured linear trends, $trendm_t$ and $trendp_t$, with respective slopes $\left(b_{m1}, b_{m2,} b_{p1}, b_{p2,}\right)$ and constant terms $\left(a_{m1}, a_{m2,} a_{p1}, a_{p2}\right)$ are designed to capture progressive changes in mean and/or high magnitude events. Depending on the continuity of $trendm_t$ and $trendp_t$ around τ, the change point can be brutal, with a clear separation of two runout regimes, or just a distinction between two different slopes.

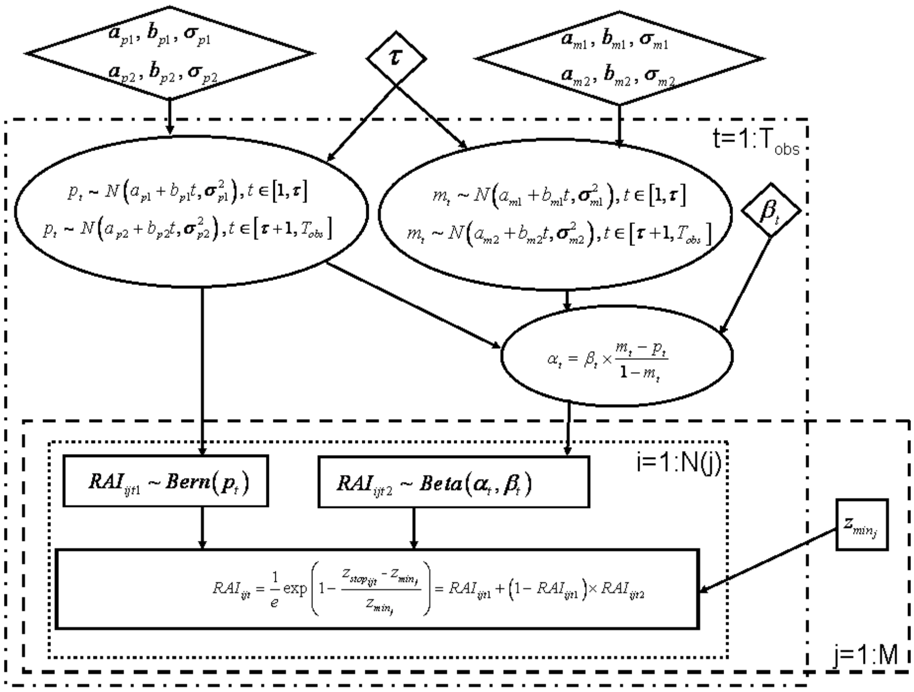

Figure 4. Change point model for mean and extreme snow avalanche runout altitudes

4.2. Application

Figure 2 (middle) shows that the mean RAI, m_t, increases slowly during nearly the first half of the studied period, and then decreases slowly to reach its initial state again. The p_t's are nearly constant during the period 1946–1976, increase to around 0.25 over a few years, and then decrease continuously and relatively strongly until 2005 (Figure 2, bottom). There is therefore evidence in both time series that a change point seems to have occurred at the middle of the studied period, with τ =1976 being the preferred year of change. All slopes except b_{p1} are significantly non-zero at the 95% credibility level, and both linear trends are nearly continuous around τ (Figure 3, middle and bottom). The two linear trends explain 53–82% of the variability of mean- and high-magnitude events, depending on the period considered. These high values indicate that the underlying linear trends significantly quantify the variations of mean- and high-magnitude avalanche runout altitudes in France during the studied period before and after the change point.

Obtaining the mean runout altitude fluctuations implies inverting the RAI. This highlights that, in contrast to the mean annual probability of reaching the valley floor, the mean annual runout altitude computed with our model depends on the path considered. With the mean altitude of the valley floor, 1223.3 m asl, the mean behavior at the state level is obtained. Under this assumption, the mean runout altitude has decreased, from a little more than 1400 m asl in 1946 to nearly 1350 m asl in 1977. Since the change point, it has increased again, up to nearly 1400 m asl in 2005. The mean avalanche runout altitude is therefore not different for now than it was 60 years ago in France. However, a clear increase seems to be engaged for nearly 30 years, which is consistent with the general context of climate warming. Moreover, the 1960s and 1970s in France were a short cold period differing from the general context of glacial retreat since the end of the Little Ice Age, which is also coherent with the decrease of mean runout altitudes at that time. These results give good confidence in the ability of the mean RIA to be a meaningful climatic indicator. For the probability of reaching the valley floor, the decrease is strong and continuous since the change point. If the return period corresponding to the valley floor is computes, it appears that it has increased from 20 years in 1980 to nearly 40 years in 2005. The same minimal altitude from a French path is now reached two times less often than 25 years ago. This is important in terms of hazard mitigation, since it suggests that French mountain valleys are now globally less exposed to avalanche hazard than they were earlier. For instance, this indicates that the usual assumption of an underlying stationary process while computing reference scenarios from the available data may lead to over-pessimistic decisions.

5. DISCUSSION AND CONCLUSION

In the previous sections, a local and small scale approach and a more global approach have been proposed for capturing annual patterns in snow avalanche occurrences and runout altitudes. The two analyzed data sets are not fully coherent (northern French Alps versus the entire French territory), but certain similarities exist in terms of modelling. Totally different structured trends have been obtained. Empirical correlations between estimates are therefore very low, both for annual and structured trends. The only exception is that the mean RAI strongly depends on the annual probability of reaching the valley floor; so that the correlation coefficient ρ equals 0.62 and 0.7 between respectively the annual and structured terms (Figure 5). This shows that avalanche occurrences and runout altitudes are influenced differently by changes in constraining climatic factors. Moreover, this indicates that the interest of a joint temporal modelling of avalanche occurrences and runout altitudes is limited, since there is little information shared by the two phenomena.

One possible explanation in accordance with Martin et al. (2001)'s work is that dry snow avalanches are progressively replaced by wet snow avalanches because of climate worming, thus keeping constant the number of events, but reducing their magnitude by modifying snow rheology. To confirm this statement, further research is needed to compare and explicitly correlate the obtained results with climatic data such temperature series. This will allow improving our knowledge on climate change in the alpine space and its consequence on avalanche hazard. Conversely, it will then also be possible to use snow avalanches as proxy indicators that point out further signals of climate change.

Finally, possible unstationarities are for the moment not taken into account in the avalanche engineering practices. Reference scenarios for hazard management are for instance always computed under the assumption of a stationary process. These results show that this should be reconsidered in the near future given the strong modification of runout altitude regime that has occurred during the last 25 years.

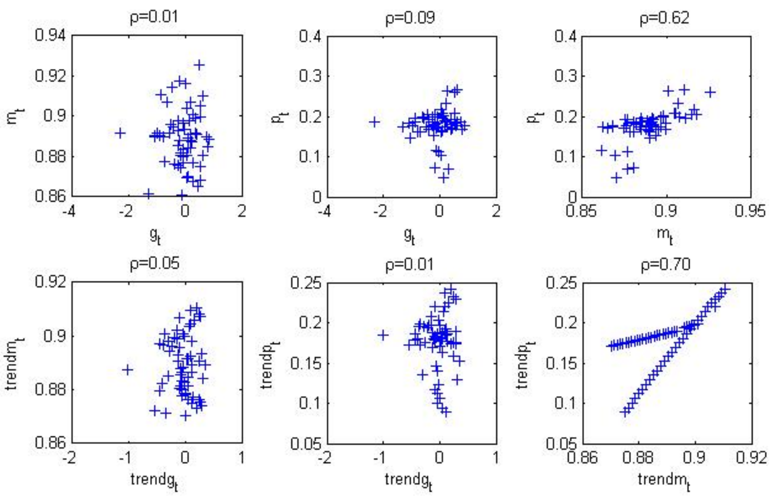

Figure 5. Scatter plots and empirical correlations between point estimates obtained with the two models

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