Earthquake Commission Biennial Research Fund 2014

Automated objective identification of seismic phases

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Introduction

The primary goal of this research project was to develop a new statistical model to categorize spatiotemporal seismic hazards holistically, using the entire earthquake record in a selected region to identify patterns correlated with subsequent large earthquakes, rather than the traditional way of hunting for individual foreshocks. Our proposed research had two interrelated and progressive objectives: 1) to extend the temporal hidden Markov models, which was developed for modeling long-term seismic cycles[1], by including earthquake magnitudes and the spatial variation in the seismic activity, which may allow us to capture more detailed seismic phase transitions; 2) use the new model to investigate and compare the earthquake patterns in long-term seismic activity.

Report

We have developed two classes of models: 1) the Markov modulated Hawkes processes with event magnitudes as marks (MMHPM), and 2) and spatiotemporal MMHPM. We derived an estimation procedure for the parameters of the two classes of models and wrote an R package for implementing this estimation procedure. The R package (MMHP) will be released to the R-CRAN site for open access.

One point to note is that, due to the complexity of the models, the estimation algorithm takes a long time for each model fit, especially when more states are included in the model. We have investigated the possibility of parallel computation and the use of computation via graphical processing units. We managed to use the computational resources from the Centre for eResearch (part of the New Zealand eScience Infrastructure, NeSI), which greatly sped up the computations.

We applied the newly developed models to the earthquake sequences at the Middle America Trench, a subduction zone, between latitudes 15 and 20, and longitudes -105 and -95 from 1 January 1976 to 31 December 2014; and from Northern California (including Parkfield) between latitudes 35 and 39 and longitudes -123 and -120, a strike-slip environment, from 1 January 1976 to 31 December 2014. Both data sets were obtained from the Advanced National Seismic System (ANSS) catalogue (http://www.ncedc.org/anss/catalog-search.html). We compared the features of the seismicity captured by the models for the two catalogues. The results from the data analysis suggest that the MMHPMs perform better than the original temporal MMHP in capturing the occurrence patterns of earthquakes. This means that the magnitudes carry information beyond that expressed simply by the greater number of triggered events used as a signal by our earlier work. The new model with magnitudes as marks is particularly effective in capturing the behaviour of several of the major earthquakes and their immediate offspring. The states discriminate between different types of clustering behaviour. Background activity, mainshocks and aftershocks all have identifiable states in both the MAT and NCA studies, allowing the transitions between, and activity within them to be quantified. At the MAT, a precursory state was visible, but in NCA, the additional states represent a second longer aftershock period and a composite foreshock/minor mainshock/major aftershock state. The spatial model naturally suffers from reduced temporal resolution compared to the purely temporal model. We again saw a background and aftershock state, but the remaining three states in the preferred model formed a sub-system with preferential transitions among themselves. Two of the three states exhibited some precursory character, one concentrated in time and space, the other much more diffuse. The former corresponds more to traditional foreshock activity, and the latter to static triggering.

We have drafted a manuscript on the development of the models and the data analysis. We will revise this manuscript and then submit it to an international journal. We also investigated the suitability of the method on the Christchurch earthquake catalogue. Due partly to the incompleteness and inhomogeneity, but largely the fact that this catalogue contains too few repeated mainshock-aftershock sequences, it is difficult to obtain reliable estimates.

PI Wang has presented this research in the meeting of the Collaboratory for the Study of Earthquake Predictability (CSEP) in Japan, 2014. Wang also discussed this research with scientists in the Istituto di Matematica Applicata e Tecnologie Informatiche, Milan, Italy and the Institute of Statistical Mathematics, Tokyo, Japan (see Outputs List). The University of Otago Research Highlights He Kitenga featured this research project (http://www.otago.ac.nz/hekitenga/2014/otago087777.html). Wang and AI Gerstenberger were both interviewed by the Dominion Post on May 11 2015 (http://www.stuff.co.nz/dominion-post/news/68435768/foreshocks-could-help-earthquake-prediction).

We mentioned above about the computational costs of these continuous-time models. A promising alternative way of modelling the long-term spatiotemporal seismic activity is to discretise the time and use a zero-inflated type of model to capture the predominating time periods when there are no observed earthquakes. During this project, PI Wang obtained a catalogue of tremors in Japan (10 years of data in the Tokai region) from Professor Kazushige Obara in the Earthquake Research Institute at the University of Tokyo. This data set contains many cycles of spatial migration of seismic events. We developed this discrete-time hidden Markov model combined with a Bernoulli distribution capturing whether an event is observed or not. This turns out to require a lot less computational resource. Different hidden states can then be used to describe a variety of clustering patterns at different locations. Wang collaborated with Professor Kazushige Obara and Associate Professor Hiroshi Tsuruoka at the University of Tokyo, and Associate Professor Jiancang Zhuang in the Institute of Statistical Mathematics in Japan, in developing a hidden Markov model to analyse the spatiotemporal migration of the events. The results shed light on how tremor locations can be classified into different clusters and the temporal pattern of the migration between these clusters. The model has been implemented as an R package (HMMextra0s) and will be submitted to the R-CRAN site for open access. This work has been submitted for publication to the Journal of the Royal Statistical Society: Series C, and is currently under review (see Outputs List). This research has been presented in the 9th International Workshop on Statistical Seismology, Potsdam, Germany as an invited talk, and the AGU Fall 2015 Meeting, San Francisco, California as a poster (see Outputs List).

This project has seen a promising start, and the genesis of many future possibilities, in modelling long-term seismic activity. Future research based on the findings from this project will investigate discretizing the earthquake catalogue and using hidden Markov models incorporating time series techniques, such as autoregressive models, to describe the triggering behaviour of earthquakes.

References

[1] Wang, T., Bebbington, M., and Harte, D. (2012). Markov-modulated Hawkes process with stepwise decay. Annals of the Institute of Statistical Mathematics, 64:521–544.

Outputs during this project

Journal articles

Paper submitted during this project:

T. Wang, J. Zhuang, K. Obara and H. Tsuruoka, Hidden Markov modeling of sparse time series from non-volcanic tremor observations. Journal of the Royal Statistical Society: Series C, under review.

Paper in preparation:

T. Wang, M. Bebbington, Markov-modulated Hawkes process with marks for long-term seismicity, to be submitted.

Software packages

R package: MMHP

R package: HMMextra0s

Conference presentations

Invited talk

T. Wang (2015) Hidden Markov modelling of sparse time series from non-volcanic tremor observations. The 9th International Workshop on Statistical Seismology, Potsdam, Germany. https://statsei9.quake.gfz-potsdam.de/doku.php?id=start

Poster

J. Zhuang, T. Wang, K. Obara and H. Tsuruoka (2015) Identifying spatiotemporal migration patterns of non-volcanic tremors using hidden Markov models, AGU Fall 2015 Meeting, San Francisco, California. http://fallmeeting.agu.org/2015/

Invited Seminars

T. Wang (2016) Identification of seismic phases using Markov-modulated marked Hawkes processes. Institute of Statistical Mathematics, Tokyo, Japan.

T. Wang (2014) Modelling of seismic activity using Markov-modulated Hawkes process and its extensions. Istituto di Matematica Applicata e Tecnologie Informatiche, Milan, Italy.