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Probabilistic modelling of sedimentary basin evolution using Bayeslands

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SUMMARY

Badlands is a basin and landscape evolution forward model for simulating the evolution of surface topography, sediment transport and sedimentation at a large range of spatial and time scales. Here we use the Bayesian paradigm to find the best-fit parameters driving basin evolution models using Badlands. Inference in a Bayesian framework is obtained via the modelled distribution of the unknown parameters. We implement parallel tempering Markov chain Monte Carlo (PT-MCMC) using high performance computing to accelerate parameter space exploration of the computationally expensive Badlands model. Our results show that traditional implementations of single chain MCMCs rarely converge and lead to misleading inference. In contrast, PT-MCMC not only reduces the computation time, but also provides a means to improve the sampling for multi-modal posterior distributions. This motivates its usage in regional basin and landscape evolution models, allowing us to determine the relative importance of different parameters driving basin stratigraphic evolution. Parameters that can be explored include time-dependent tectonic and dynamic topography, precipitation, rock erodibility, flexural rigidity of the lithosphere and relative sea level fluctuations.

Key words: Basin evolution, stratigraphy, Bayesian inference, Parallel tempering, Badlands, Bayeslands

INTRODUCTION

This paper reviews Bayeslands, a framework for inference and uncertainty quantification in the Badlands model for basin and landscape evolution (Salles et al., 2018). We review the performance of Bayeslands in terms of prediction accuracy of present-day topography and sediment deposition over time to understand what drives the stratigraphic evolution of a given sedimentary basin.

The Bayesian framework provides a logically consistent mechanism for fusing information from various sources to provide meaningful inference. The prior distribution is a mechanism to incorporate information from previous research and expert opinion, and the likelihood is a mechanism to incorporate information from data. The ability to fuse information from many sources in a principled fashion has made Bayesian inference an increasingly popular choice for the estimation and uncertainty quantification of parameters in complex models (Robert and Casella, 2011). The task of estimating parameters in geophysical models is also known as Bayesian inversion.

Although Bayesian inversion has become popular in geophysics in the past few decades (Sambridge, 1999), estimating the free parameters of a given model (posterior distribution) is often nontrivial. Markov chain Monte Carlo (MCMC) sampling methods are commonly used for estimation. They face a number of challenges of which some are effective distributions of initial model parameters and multi-modal surfaces in a multi-parameter space. So-called parallel tempering (PT-MCMC) is a simulation method aimed at improving the dynamic properties of Monte Carlo method simulations of physical systems. The potential for PT-MCMC in geoscience has been demonstrated for complex multi-modal problems (Sambridge, 2013).

Basin and landscape evolution models are characterized by parameters that interact in a complicated fashion and feature a high dimensional parameter space given time dependent parameters that represent climate factors for thousands to millions of years (Salles and Hardiman, 2016). Basin and landscape dynamics (Badlands) is an unusual example of a landscape evolution model for not only simulating topography development through time, but also tracking sediments from source to sink with the capability to create synthetic basin stratigraphies (Salles et al., 2018). Badlands models feature a number of unknown parameters which need to be estimated given incomplete and sparse observational datasets which remains a major challenge in the field.

In our previous work, we developed the Bayeslands framework using a canonical MCMC method for inference of two selected parameters in the Badlands model [Chandra et al., 2018a]. Bayeslands demonstrated that the posterior surface of selected parameters could exhibit highly irregular features, such as multi-modality and discontinuities which made it difficult for sampling. An improved approach known as PT-Bayeslands provides enhanced exploration features for uncertainty quantification and estimation of selected parameters for Badlands model (Chandra et al., 2018b). PT-Bayeslands improves computational performance using the power of parallel computing where different components of the algorithm are executed on separate courses (replicas) in a high performance computing framework.

In this paper, we review PT-Bayeslands for a selected continental margin problem taken from South Island, New Zealand and provide preliminary results for parameter estimation and uncertainty quantification.

METHOD AND RESULTS

Bayeslands: Proof of concept

Badlands facilitates forward stratigraphic modelling that takes an initial topography and a set of parameters, denoted by as inputs, to produce a series of consequent topographies at given time intervals. Here we assume the final topography is the only topography that we are able to observe and therefore the task of making inference about the landscape evolution over time is very difficult. The input parameters include, *precipitation*: temporal variations in precipitation as a constant value (metres per year), *erodibility*: The erodibility coefficient is scale-dependent and its value depends on lithology, channel width, flood frequency, channel hydraulics, and the parameters *m and n* which indicate how the incision rate scales with bed shear stress for constant values of sediment flux and sediment transport capacity. Generally, *m* and *n* are both positive, and their ratio (m/n) is considered to be close to 0.5. Other relevant parameters are the linear slope diffusion parameters *caerial* and *cmarine,* where parameterisation of the sediment transport includes the simple creep transport law which states that transport rate depends linearly on topographic gradient (Salles et al., 2018). The marine and surface parameters govern the long-term hillslope processes acting on any landscape.

Using Badlands, we simulate the geomorphological evolution over one million years of a location on the northeastern margin of the South Island of New Zealand as shown by the red rectangular box in Figure 1. This region is represented by a grid of 91 x 81 points that cover 136 by 123 kilometers squared;

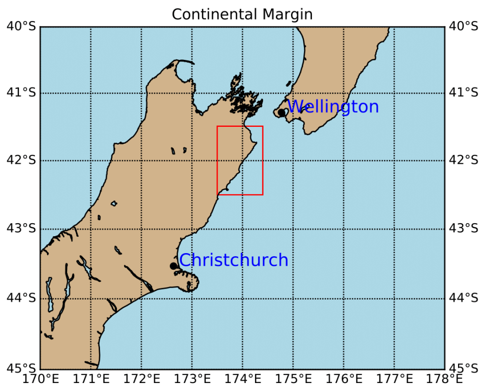


Figure 1. Selected Continental-Margin problem from the South Island of New Zealand, outlined by the red rectangle.

RESULTS AND DISCUSSION

The performance of PT-Bayelands is evaluated by comparison of the parameter estimates inferred by PT-Bayeslands to those used in the generation of the simulated or present-day data, as well as the quality of predictions for sediment deposition in the basins and the elevation landscape in comparison with the ground truth data.

Figure 4, is a histogram estimate of the posterior distribution for precipitation which is one of the parameters inferred by Bayeslands. Note that the vertical line in red in the figure shows the true value of the parameter used to generate the simulated topography. A major goal of the experiments was to check if the Bayeslands framework is able to recover the true value of the parameters. We find that the MCMC sampling estimate of the posterior distribution is reasonable. Figure 5 shows the six parameters that were inferred from the synthetic continental margin problem.

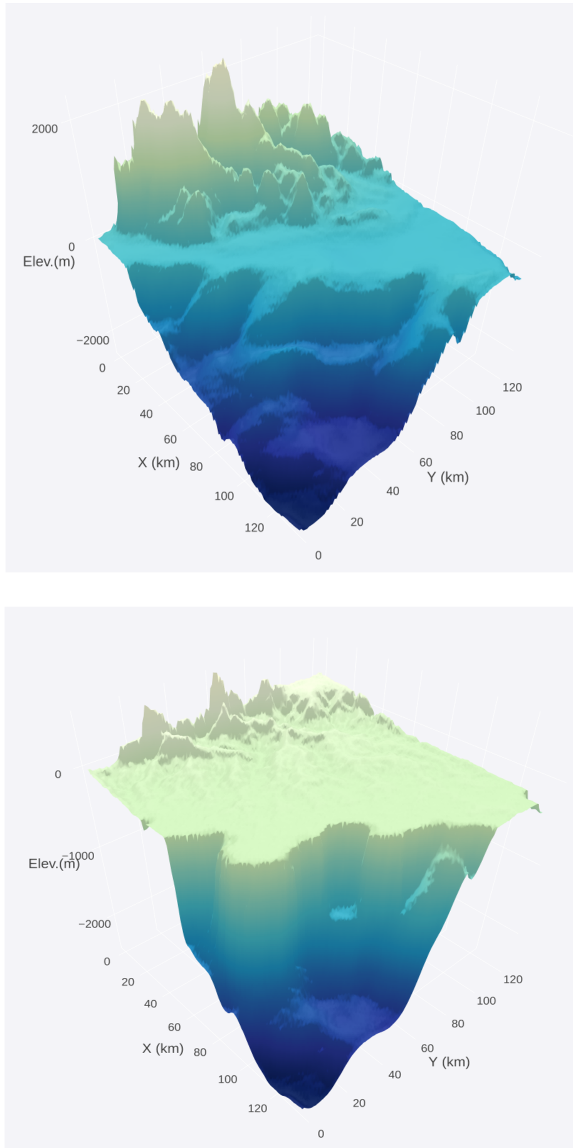


Figure 2. Continental-Margin initial (top) and simulated topography (bottom) after one million years of evolution. We use this the simulated topography as our synthetic ground truth topography

Figure 6 shows a cross section with uncertainty quantification of the predicted elevation of the continental margin topography. The coloured portion displays the 95% credible interval which highlights the uncertainty in the predictions.

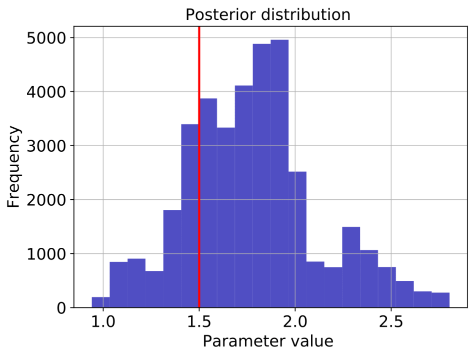


Figure 4. The panels show estimates of the posterior distribution and trace-plot of the precipitation parameter. The true value is given by a red vertical line.

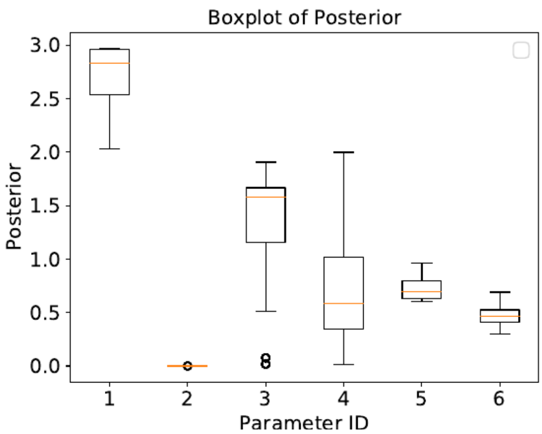


Figure 5. Boxplot of posterior for 6 parameters. The parameter IDs are: 1. precipitation, 2. erodibility 3. m-value, 4. n-value, 5. marine linear slope diffusion parameter, 6. continental linear slope diffusion parameter.

Due to the issue of multi-modality in complex models, there can be a number of possible combinations of input variables that give rise to an identical elevation in the predicted topography. To constrain the number of possible combination of variables, we use information featured in the sediment erosion-deposition history. The sediment thickness history is available for each case chosen at select locations. In figure 7, the heatmap shows the change in sediment thickness at the final time interval as given by the Badlands model. The yellow dots indicate those locations where it is possible to obtain the actual sediment history. Hence, the likelihood function used in this Bayesian Inference scheme takes both the landscape topography and erosion-deposition ground-truth into account. Figure 8 shows the predicted evolution of the sediment thickness at the selected locations.

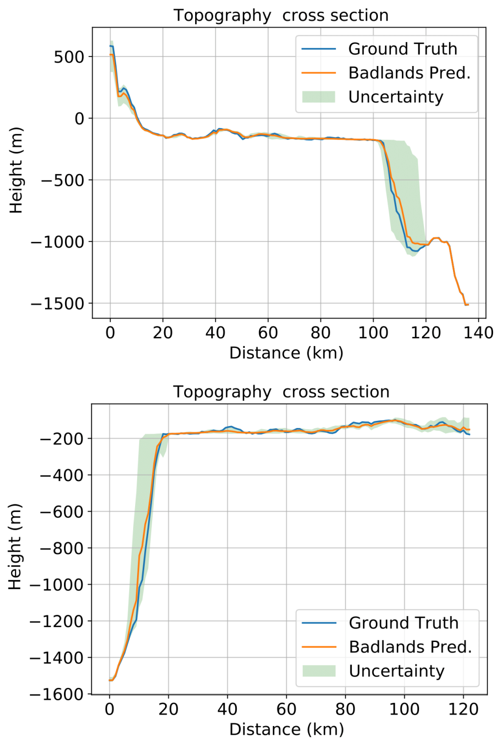


Figure 6. Cross-section comparing the ground-truth evolved topography with the PT-Bayeslands (Badlands) predictions. In these experiments, 10,000 samples produce an estimate of the mean predicted evolved topography and provide an estimate of uncertainty.

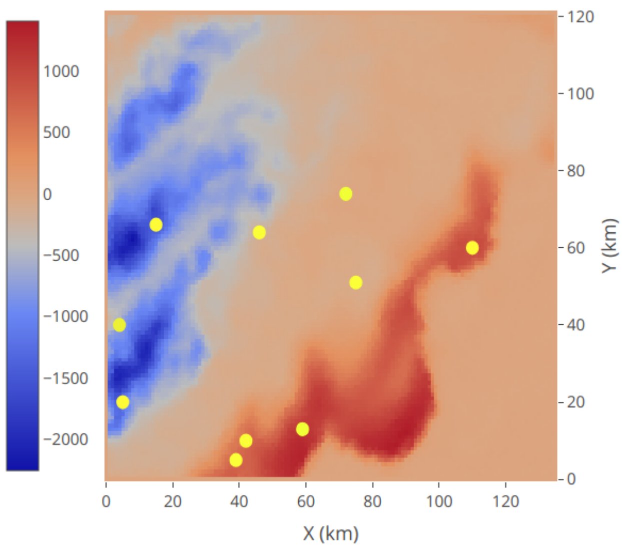


Figure 7. Map view showing evolved model sediment erosion (blue) and deposition (red). The selected locations for likelihood evaluation are overlain as yellow dots on the map.

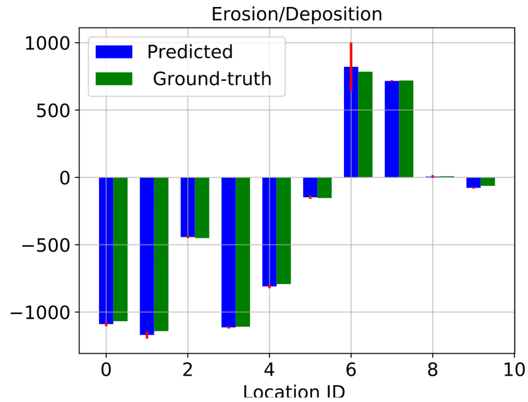
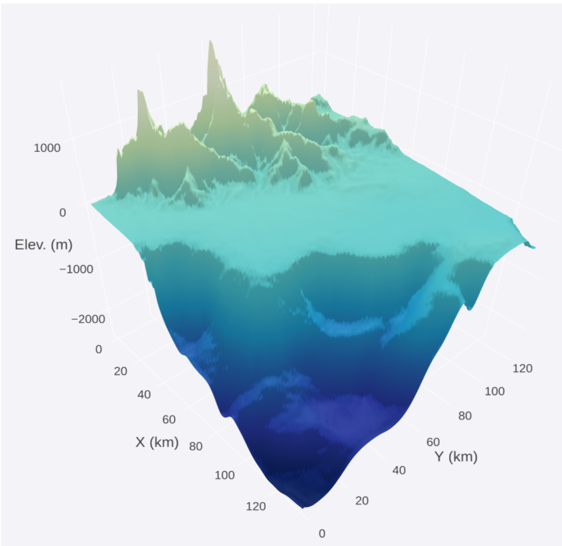
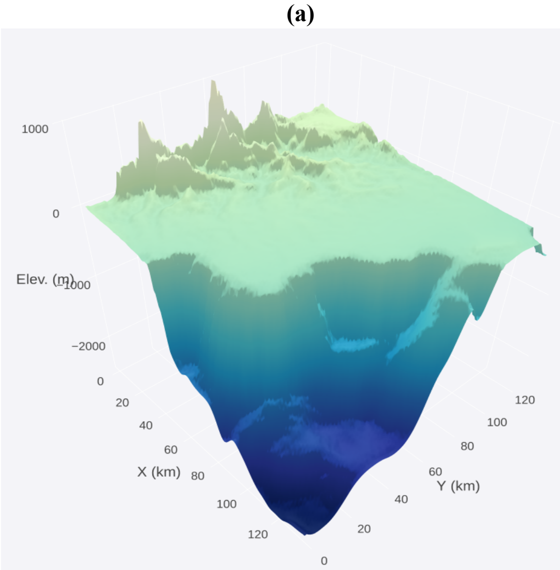


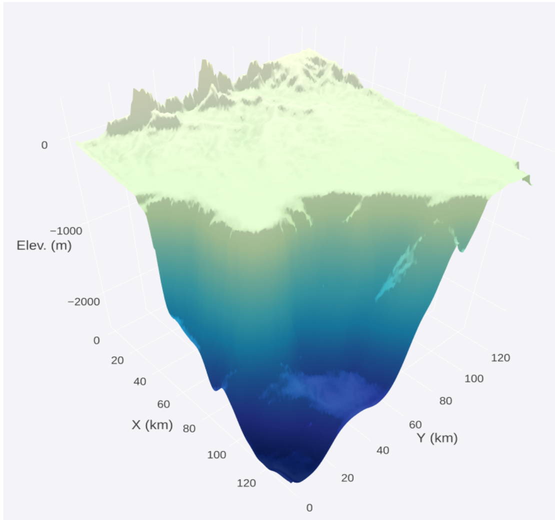
Figure 8. Badlands landscape evolution for the continental margin model illustrating total sediment deposition for 10 selected points on the topography.



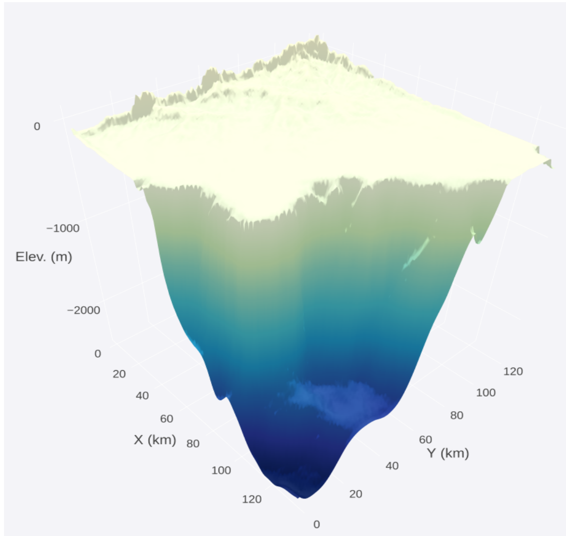
(a)



(b)



(c)



(d)

Figure 9. CM topography evolution over time at selected intervals over a million years. (a) 250,000 years; (b) 500,000 years; (c) 750,000 years; (d) 1,000,000 years.

Figure 9 shows an example of the topographies produced by Badlands at selected time intervals.

CONCLUSIONS AND FUTURE WORK

The Bayeslands framework provides a rigorous approach for estimation and uncertainty quantification of key parameters in basin and landscape dynamics models (Badlands) using a parallel implemented and computationally fast framework. The results show that the method provides a means to explore a highly irregular multi-modal parameter space. This improves the accuracy of predicting elevation and sediment deposition.

Future work will extend the method for a larger number of parameters that includes spatio-temporal variations in precipitation and uplift for different timescales and regions. Moreover, for large-scale or continental-scale problems, it would be reasonable to implement further enhancements to the method for lowering the overall computational time. This could be done through surrogate-assisted models where a

surrogate of Badlands, implemented via machine learning, helps evaluate the model performance. Further, efficient gradient free proposal scheme used in the MCMC algorithm need to be implemented as the number of parameters and the complexity of the model increases.

Continents and sedimentary basins have moved through different climate belts through time, due to plate motions as well as long-term climate change. In addition, rocks with different erodibility values might have been exposed at the surface through time. Therefore, in the future we will implement region and time-dependent constraints for these parameters to consider spatio-temporal variations in erosion and sediment flux into sedimentary basins, creating synthetic stratigraphies that can be ground-truthed against observed basin stratigraphy.

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