Analyzing Catalogs With Unsupervised Machine Learning To Reveal Long-range Spatio-temporal Predictive Structure In Global Seismicity

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Summary: ***Using a new approach to unsupervised abductive learning[1] on historical records of seismic events, we recover long-range spatio-temporal structure in global seismicity. Our approach is knowledge-free; we do not inject any a priori knowledge of seismic stress propagation dynamics, nor do we assume any model of rheology, or constrain the analysis in any way with an a priori expectation of the physics in play. Our technique allows us to consider the data, and only the data; and distill hidden predictive patterns in the observed seismicity. Free from the need to instill a priori models, there are no parameters to tune, or physical constants to set. Our results indicate causal connections between seismic dynamics observed in California to that on the eastern edge of the Pacific plate, and additionally such hidden connections is shown to exist between events temporally separated by nearly a decade. Our technique allows for short-term earthquake prediction as well, and we establish non-trivial performance above random decisions.***

Motivation: The idea of faults interacting across large spatial distances and over large time intervals has been proposed recently;[2]–[7] and has been met with some controversy.[8] This is based, on one hand, on simulation of elaborate visco-elastic stress models with specified rheology that demonstrate long-range propagation of postseismic stresses, and on the other hand on the demonstrated deviation of the statistical characteristics of global seismicity before and after large events.[7] Skepticism about the existence of such long-range spatio-temporal interactions primarily arises from a lack of convincing phenomenological evidence;[5] notably the current body of evidence often relates to specific historical cases.[9]

Detailed objective analysis of the historical data on a global scale would definitively resolve this debate. However, with the exception of some preliminary efforts,[10] a formal statistical calculation performed on worldwide seismic historical data is still lacking. This deficiency reflects the general difficulty faced by state of the art analysis tools in verifying long-range dependency in limited amounts of spatio-temporal data generated by complex stochastic dynamical systems (as opposed to verifying simulation results with assumed models).

Approach: We solve this problem via unsupervised machine learning on the seismic catalogs. We investigate if causal patterns exist in the historical data that would point towards long-range spatio-temporal structure in global seismicity, and whether such structure, if present, may be exploited for precise short-term prediction of seismic events. Our results indicate that the answer is affirmative on both counts.

Key Insight: Our inference algorithm infers two distinct classes of probabilistic predictors: self-models and cross-models. Self-models compress historical data on seismic activity from small seismic zones, and attempt to capture the statistical predictors that dictate future dynamics in the same zone. Cross-models attempt to capture statistically significant cross-talk between spatio-temporally non-colocated seismic zones. The automated inference produced the following fundamental insight for historical seismic data:

> *Self-models always tend to be simple; cross-models of certain pairs of streams tend to be complex.*

This implies that the seismic event sequence at a particular location often behaves as a sequence of nearly independent events, and we are fundamentally limited in how well we can predict future events with only this information; any prediction beyond the average seismicity seems difficult. However, the non-trivial structure of cross-models (corresponding often to locations separated by large distances, and large time shifts) indicate the possibility of significantly improved predictions when information from such causal inter-dependencies are fused together. Additionally, the cross-models with non-trivial structures clearly identify the seismic zones that interact.

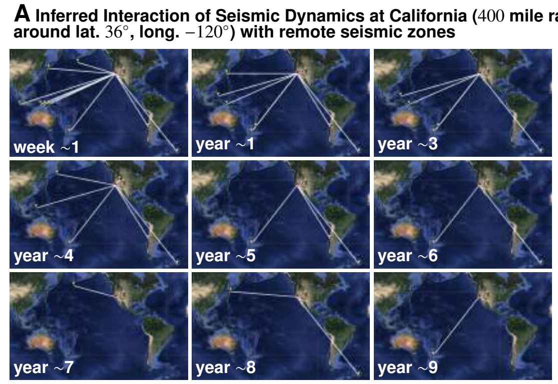

Fig. 1: **Illustration of Inferred Spatio-temporal Cross-talk.** Considering coordinates $36°N120°W$ as the center of the target zone, we infer a temporal variation in the interacting zones as shown in the montage. Importantly, the interactions appear to die off beyond delays of over 9 years.

Brief Overview Of Results: Our analysis yields the following results:

- Seismic zones do indeed interact across large spatial distances.
- Seismic interaction has long-term memory, and in the instance illustrated in Fig. 1, it fades after around ~ 9 years, which matches up well with predictions from visco-elastic modeling.
- The specific seismic zones that interact often vary with the time-interval between the interactions (See montage in Fig. 1)
- Memory is shown to fade exponentially fast with time.
- The spatio-temporal interactions may be effectively used for short-range prediction. The predictions are not perfect, but we are able to achieve a ROC area of 0.72.
- One important feature of our inference algorithm is that modeling error in constructing the models is measurable independently from the ROC performance. We show that the modeling error degrades linearly with increasing time delay. Recall, the change in ROC performance falls exponentially with increasing time delay.

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