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Sequential Data Assimilation for Seismicity: a Proof of Concept

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Integrating geological and geophysical observations, laboratory results and physics-based numerical modeling is crucial to improve our understanding of the occurrence of large subduction earthquakes. How to do this integration is less obvious, especially in light of the scarcity and uncertainty of natural and laboratory data and the difficulty of modeling the physics governing earthquakes. One way to efficiently combine information from these sources in order to estimate states and/or parameters is data assimilation, a mathematically sound framework extensively developed for weather forecasting purposes. We demonstrate the potential of using data assimilation by applying an Ensemble Kalman Filter to recover the current and forecast the future state of stress and strength on the megathrust based on data from a single borehole.

Data and its errors are for the first time assimilated to - using the least-squares solution of Bayes theorem - update a Partial Differential Equation-driven seismic cycle model. This visco-elasto-plastic continuum forward model solves Navier-Stokes equations with a rate-dependent friction coefficient. To prove this concept we perform a perfect model test in an analogue subduction zone setting. Synthetic numerical data from a single analogue borehole are assimilated into 150 ensemble models.

Since we know the true state of the numerical data model, a quantitative and qualitative evaluation shows that meaningful information on the stress and strength is available, even when only data from a single borehole is assimilated over only a part of a seismic cycle. This is possible, since the sampled error covariance matrix contains prior information on the physics that relates velocities, stresses, and pressures at the surface to those at the fault. During the analysis step, stress and strength distributions are thus reconstructed in such a way that fault coupling can be updated to either inhibit or trigger events. In the subsequent forward propagation step the physical equations are solved to propagate the updated states forward in time and thus provide probabilistic information on the occurrence of the next analogue earthquake. At the next assimilation step(s), the systems forecasting ability turns out to be distinctly better than using a periodic model to forecast this simple, quasi-periodic sequence. Combining our knowledge of physical laws with observations thus seems to be a useful tool that could be used to improve probabilistic seismic hazard assessment and increase our physical understanding of the spatiotemporal occurrence of earthquakes, subduction zones, and other Solid Earth systems.