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Sequential Data Assimilation for Seismicity: a Proof of Concept

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Our probabilistic forecasting ability and physical understanding of earthquakes is significantly hampered by limited indications on the current and evolving state of stress and strength on faults. This information is typically thought to be beyond our resolution capabilities based on surface data. We show that the state of stress and strength are actually obtainable for settings with one dominant fault.

State variables and their uncertainties are obtained using Ensemble Kalman Filtering, a sequential data assimilation technique extensively developed for weather forecasting purposes. Through the least-squares solution of Bayes theorem erroneous data is for the first time assimilated to 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 (van Dinther et al., JGR, 2013). To prove the concept of this weather - earthquake forecasting bridge we perform a perfect model test. Synthetic numerical data from a single analogue borehole is assimilated into 20 ensemble models over 14 cycles of analogue earthquakes.

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 of the unobserved fault is typically already available, once data from a single, shallow borehole is assimilated over 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 constant assimilation step, the systems forecasting ability turns out to be beyond expectations; 5 analogue events are forecasted approximately accurately, 5 had indications slightly earlier, 3 were identified only during propagation, and 1 was missed. Else predominantly quite interseismic times were forecasted, but for 3 occasions where smaller events triggered prolonged probabilities until the larger event that came slightly latter. Besides temporal forecasting, we also observe some magnitude forecasting skill for 59% of the events, while the other event sizes were underestimated. This new framework thus provides potential to in the long-term assist with improving our probabilistic hazard assessment.