EGU24-11543, updated on 03 Nov 2024
https://doi.org/10.5194/egusphere-egu24-11543
EGU General Assembly 2024

Ensemble Data Assimilation with Model Error Inclusion for Estimating Fault-Slip Occurrence in Large-Scale Laboratory Experiments

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The forecasting of earthquake occurrence remains a significant challenge in seismology, primarily due to uncertainties in understanding the current state of stress, strength, and the parameters controlling the slip behaviour of faults. Among these parameters, friction parameters are crucial as they control the earthquake recurrence interval and their nucleation size. There is a critical gap in effectively integrating observational data with physics-based models, particularly in the face of parameter bias. This study addresses how ensemble data assimilation methods can be optimized to address these challenges and reduce uncertainties in fault-slip estimates.

Our objective is to enhance the accuracy of earthquake forecasting by incorporating model error into ensemble data assimilation methods, thus improving the estimation of critical state variables such as shear stress and slip velocity. We employed the Ensemble Kalman (EnKF), Adaptive Gaussian Mixture (AGMF), and Particle Flow (PFF) filters, which are integrated with earthquake sequence models. These methods were applied in two stages: 1) Perfect model experiments using 1-D Burridge-Knopoff models to assess the benefits of including model error in estimating non-periodic and chaotic behaviours in low-dimensional systems. 2) Application in a meter-scale direct-shear laboratory setup, assimilating measurements from shear-strain gauges near the fault, to examine the effects of varying normal stress profiles on the fault on the estimates and the impact of including model error.

The perfect model experiments demonstrated improved estimation of shear stress, slip velocity, and the state variable (θ), particularly in estimating non-periodic sequences and chaotic behaviour using stable periodic solutions when confronted with small parameter biases. In the laboratory setup, variations in normal stress profiles significantly influenced the information content. Sensor placement relative to the fault and seismic phase was found to critically impact the observations' informational value, with sensor proximity to the fault being a critical aspect and the information content being higher around the coseismic phase.

This research provides valuable insights into the intricate process of earthquake forecasting, underscoring the role of data-assimilation techniques in enhancing our understanding and forecasting abilities in this field.