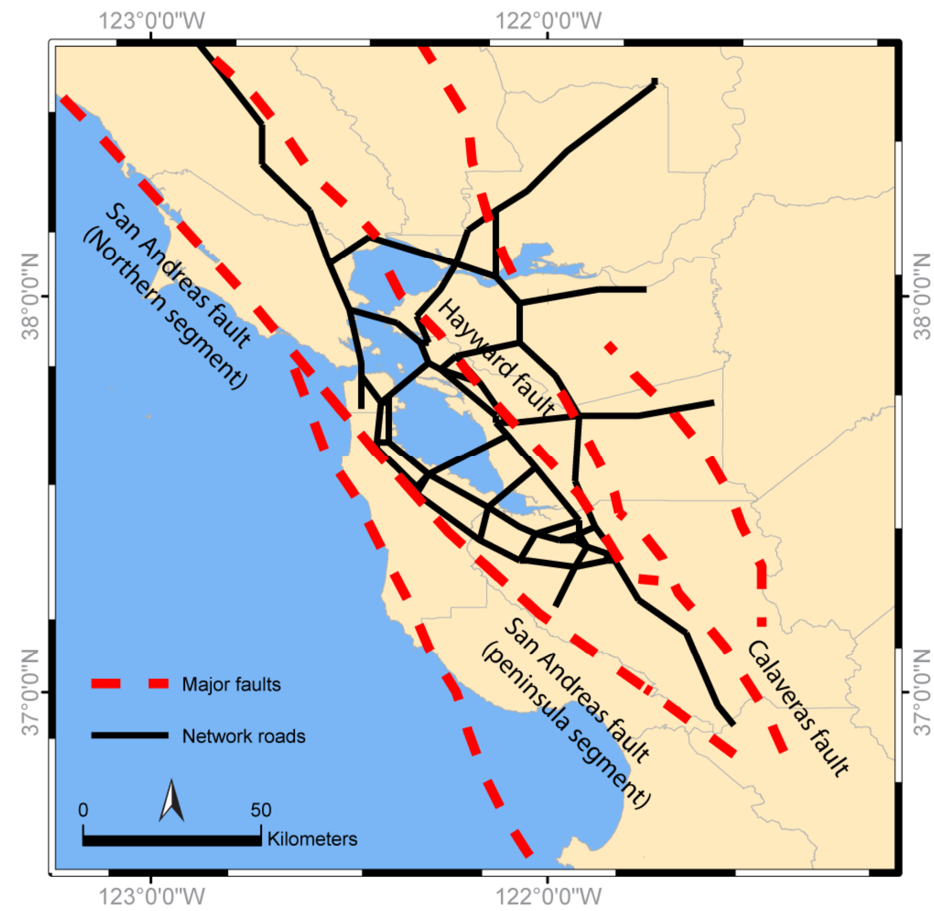
Characterizing seismic hazard to distributed systems using efficient simulation techniques

Jack Baker & Nirmal Jayaram

Civil & Environmental Engineering
Stanford University

Motivation

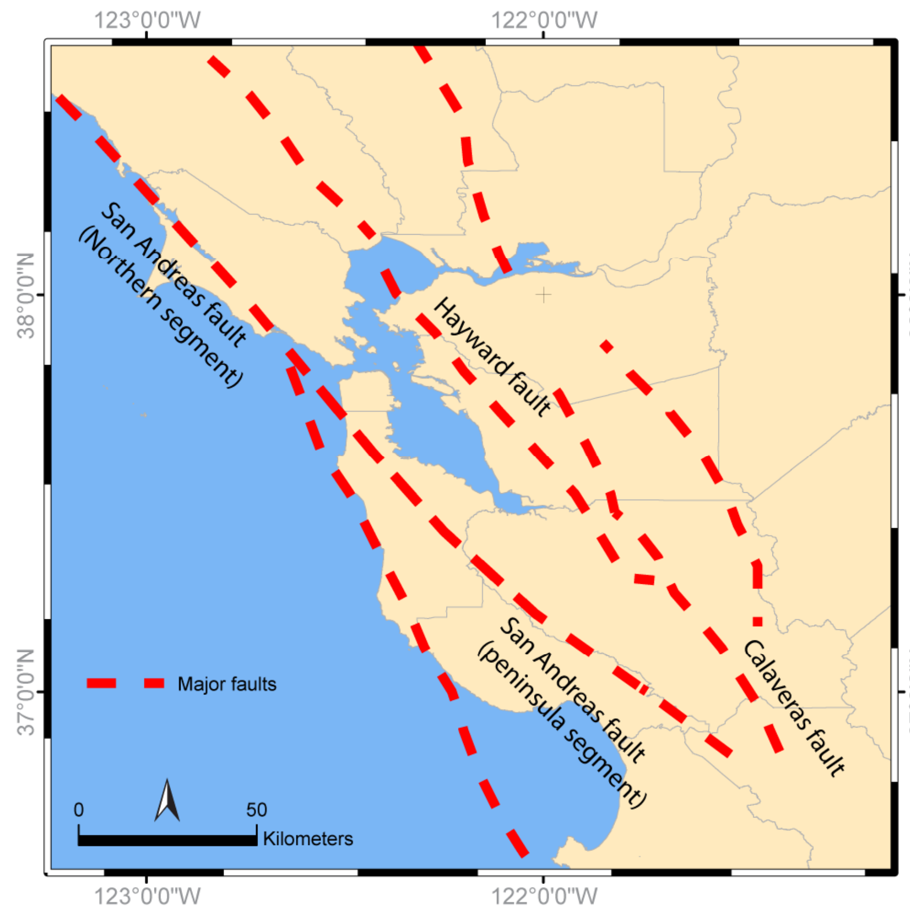
- We are interested in assessing seismic risk to distributed transportation networks
- The spatial extent of these systems is a challenge
- Spatial correlation of ground motion intensities is an important consideration for these analyses



Bay area interstate highways

Background: seismic sources

Both this work and traditional Probabilistic Seismic Hazard Analysis require seismic source characterization

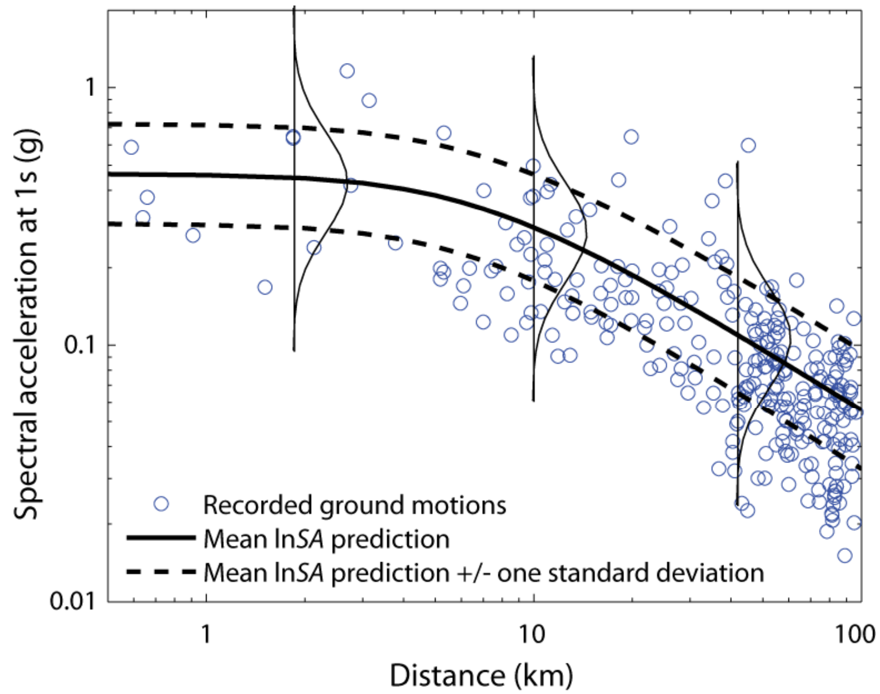


Major Bay area faults

Background: ground motion prediction

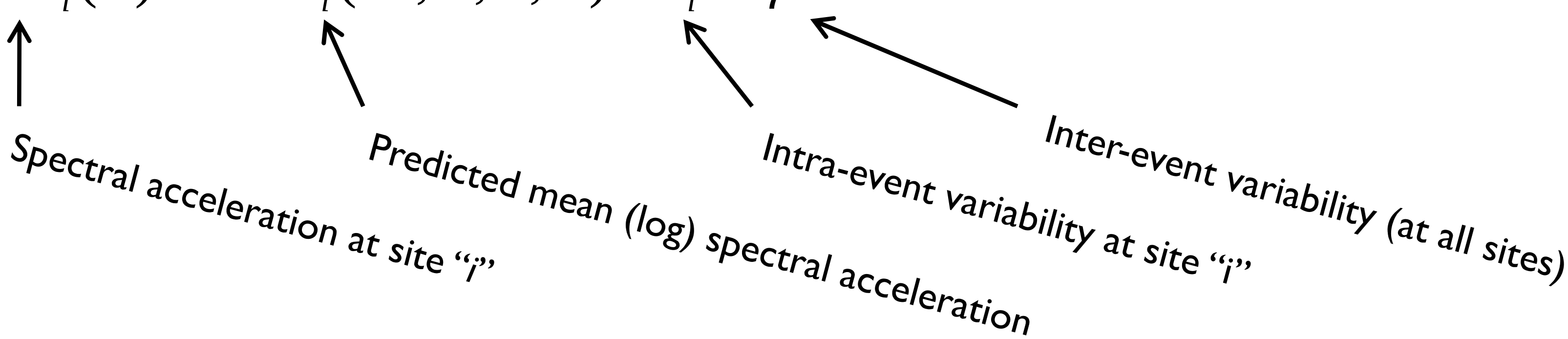
Ground Motion Prediction ("attenuation") models provide predictions of the distribution of ground motion intensity (e.g., spectral acceleration) as a function of earthquake magnitude, source-to-site distance, etc.

Observed spectral acceleration values from the 1999 Chi-Chi, Taiwan earthquake



Model form:

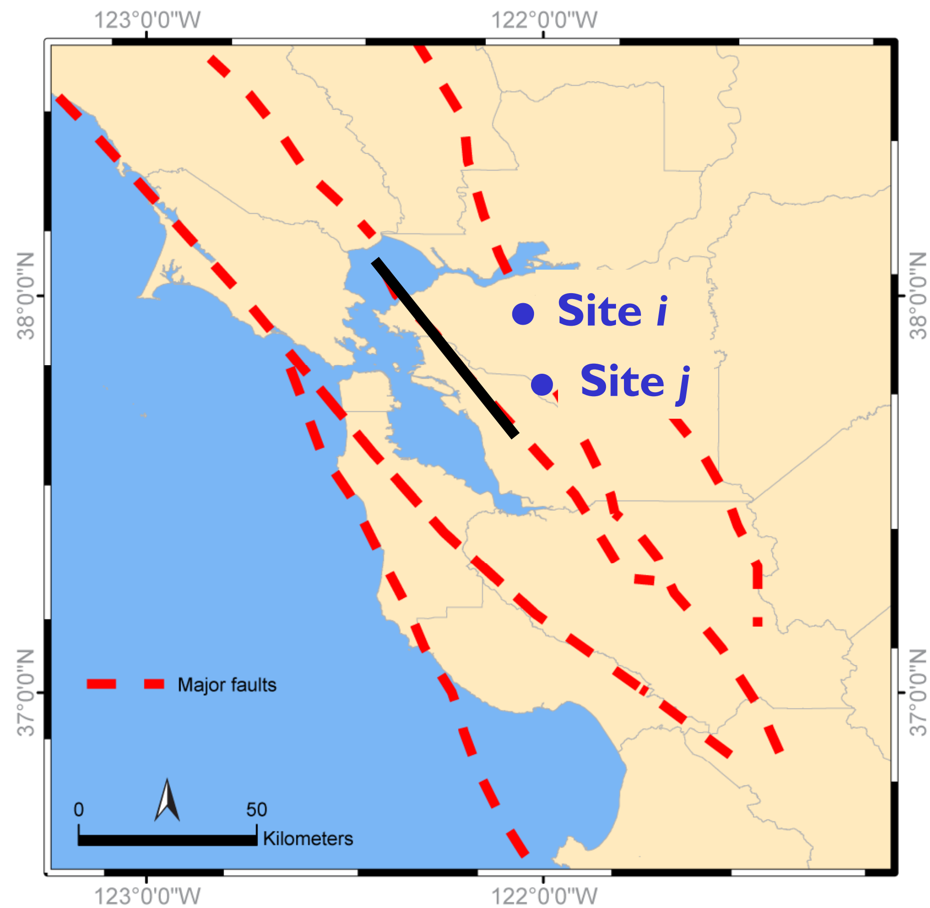
$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \varepsilon_i + \eta$$



Ground motion intensity at two sites

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R_i, T, \ldots)} + \varepsilon_i + \eta$$

$$\ln Sa_j(T) = \overline{\ln Sa_j(M, R_j, T, \ldots)} + \varepsilon_j + \eta$$



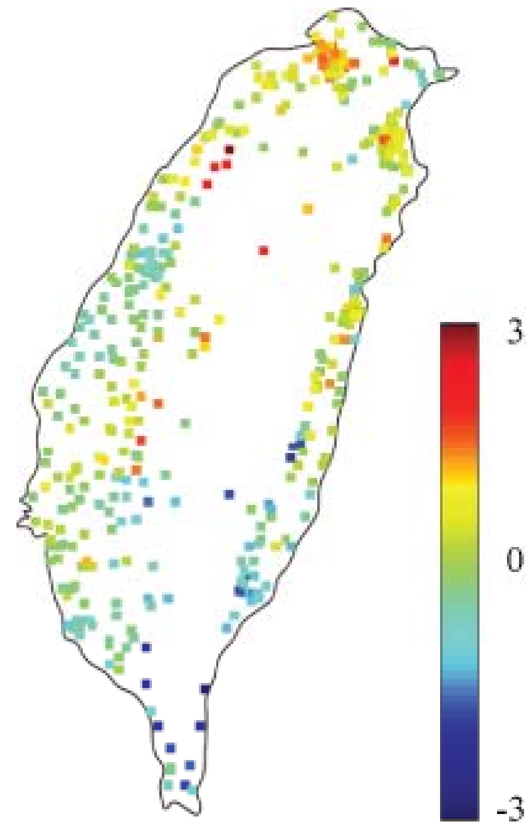
Observed "residuals" from well-recorded earthquakes

$$\varepsilon_i = \ln Sa_i(T) - \overline{\ln Sa_i(M, R_i, T, \ldots)} - \eta$$

Observations of past earthquakes shows that these residuals are correlated at nearby sites, due to

- Common source earthquake
- Similar location to asperities
- Similar wave propagation paths
- Similar local site effects

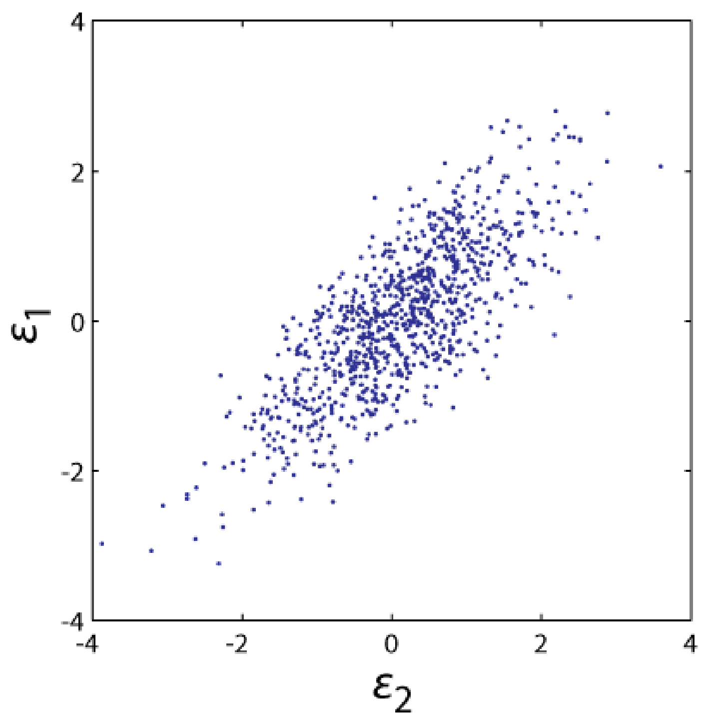
Note that this correlation is different than ground motion coherence

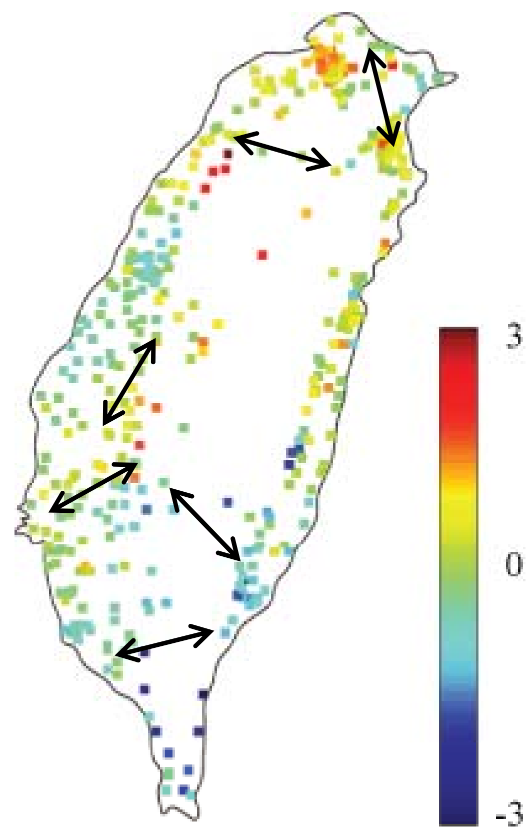


PGA ε's from the 1999 Chi-Chi earthquake

Estimation of correlation (or covariance)

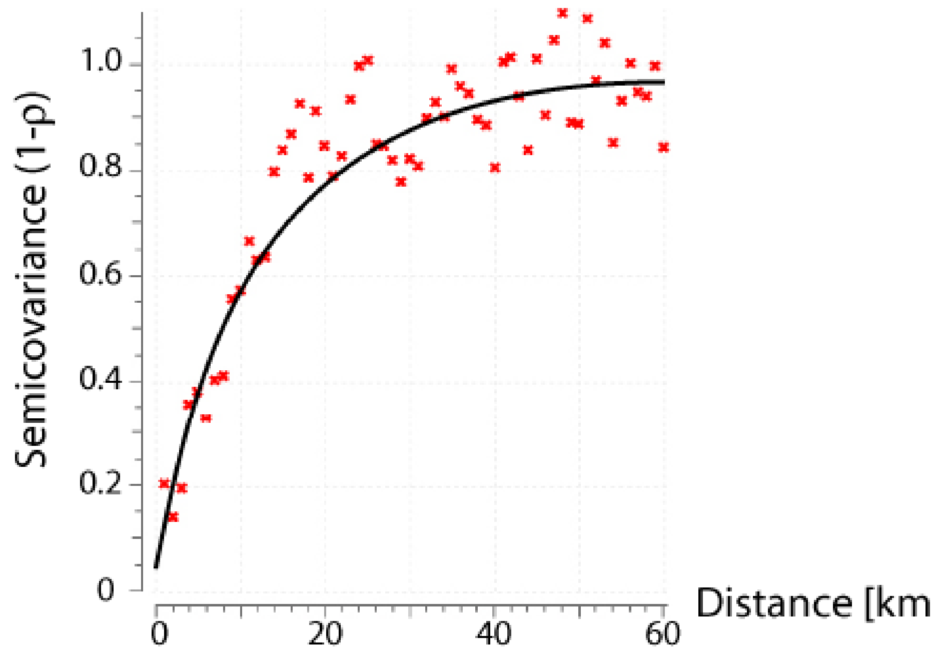
If we assume stationarity and anisotropy of the ε's, we can pool paired observations with comparable distances to estimate a correlation coefficients





Estimation of correlation from well-recorded earthquakes

We can turn these observations into a predictive model

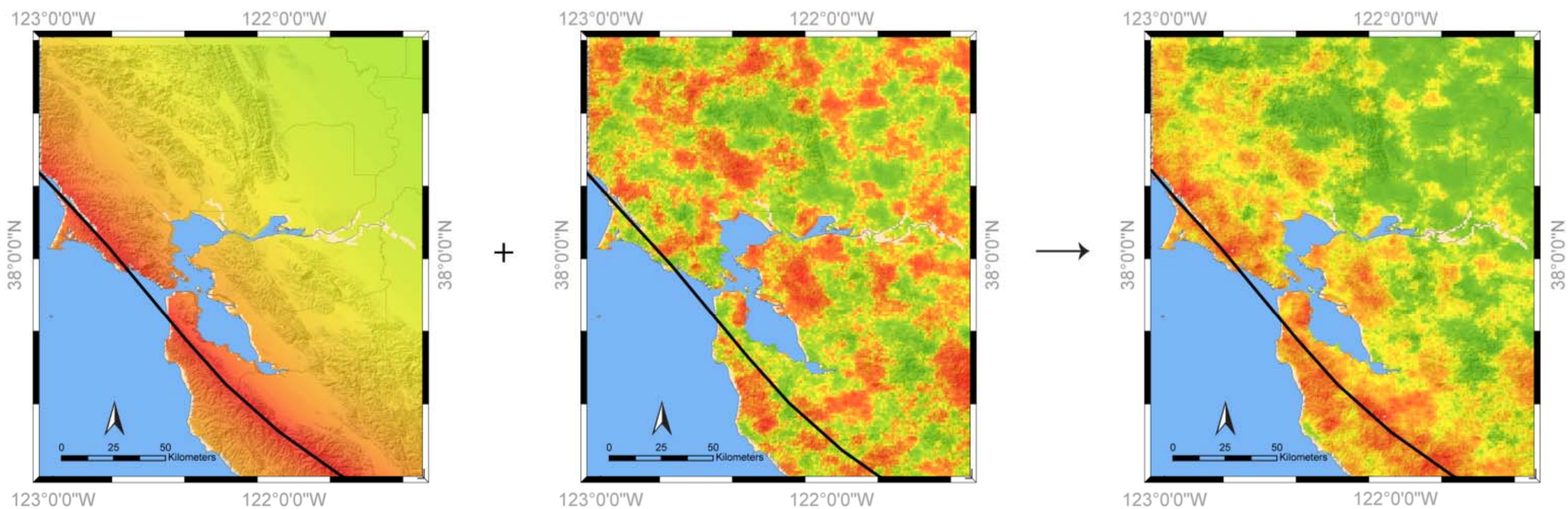


Empirical semivariogram for PGA ε's from the 1999 Chi-Chi earthquake

Application: risk to lifeline systems

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \varepsilon_i + \eta$$

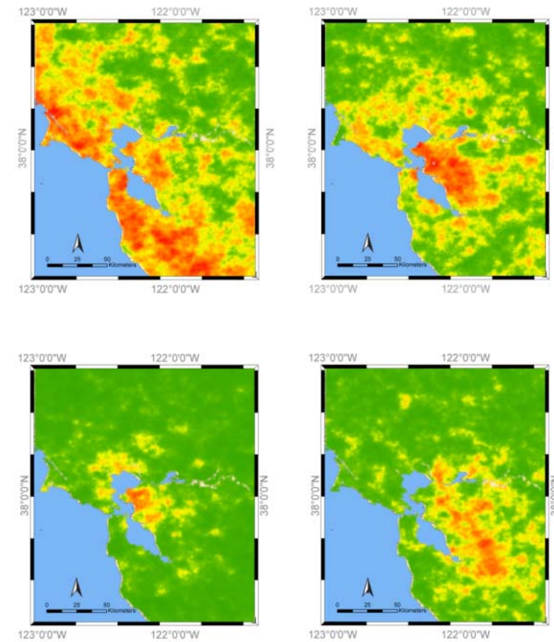
$e^{\overline{\ln Sa_i(M,R,T,\ldots)}}$ $\quad + \quad$ ε_i $\quad \longrightarrow \quad$ $Sa_i(T)$



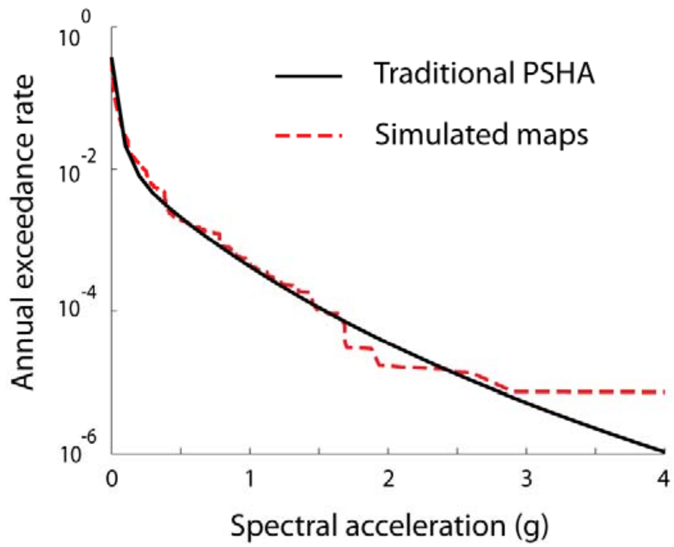
We can't produce PSHA-like maps of hazard, but we can use Monte Carlo simulations to produce a set of ground motion scenarios and associated probabilities

An aside: comparison with single-site PSHA

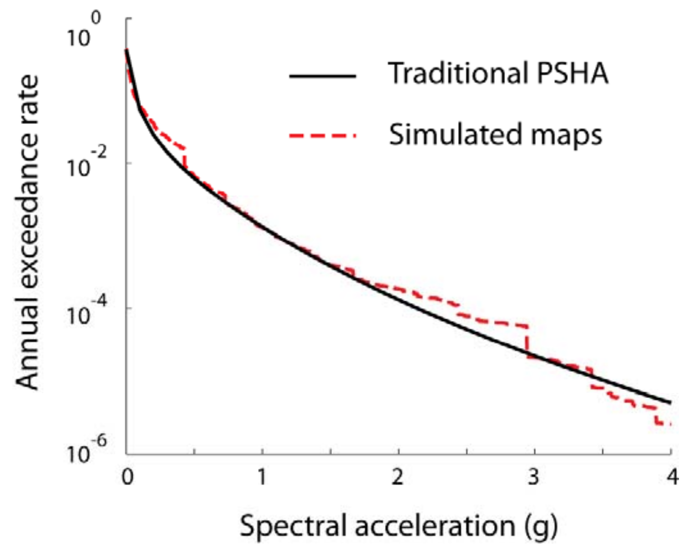
If we look at the observed *Sa* values from these simulations at any single site, they match the distribution from traditional single-site PSHA



Site A:

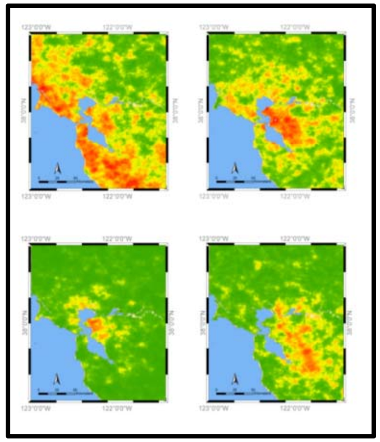


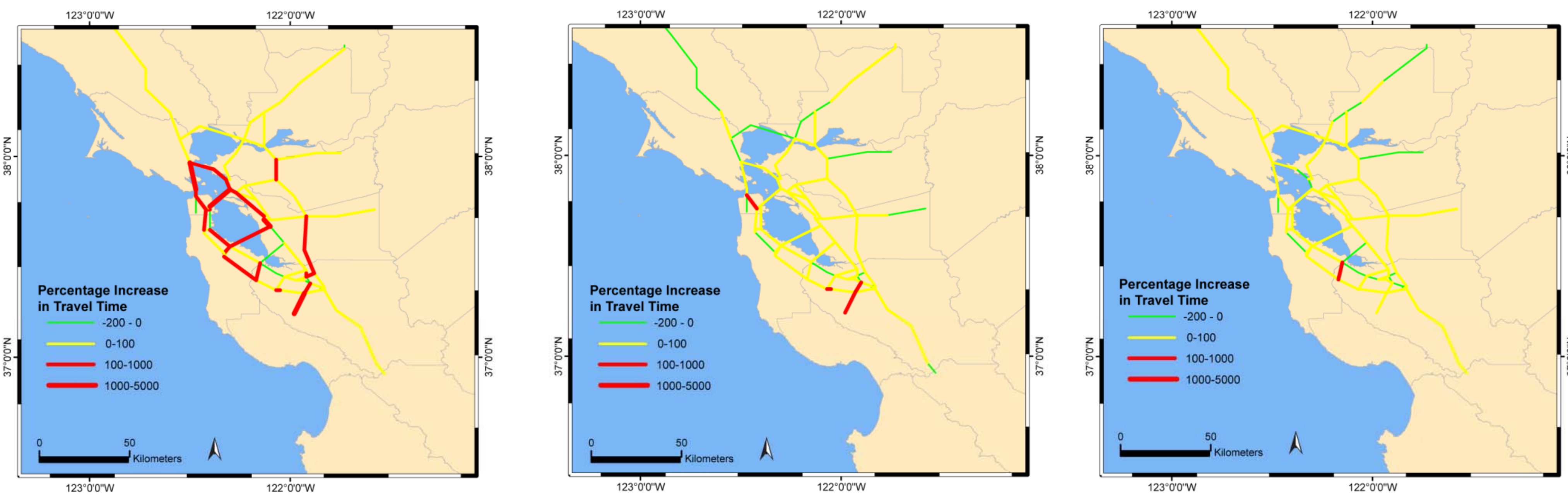
Site B:



Application: risk to lifeline systems

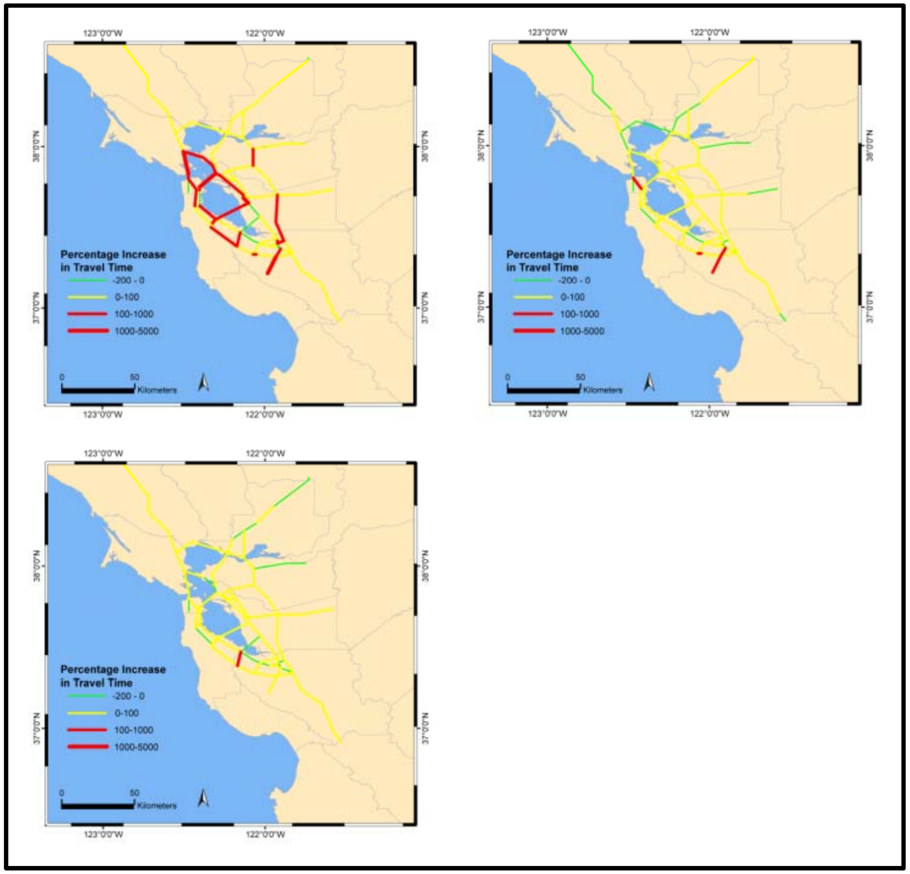
For each map of spectral accelerations, we can predict the resulting damage and disruption to our network



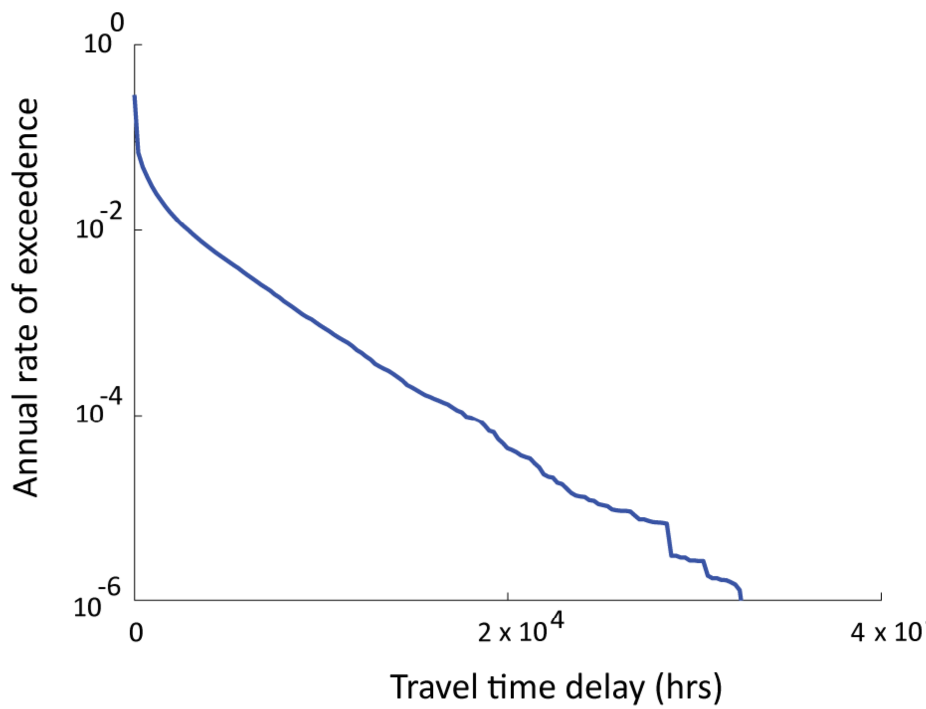


Illustrative results using a simplified highway network model

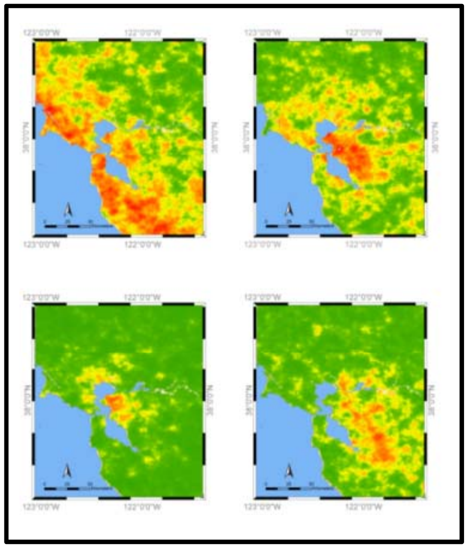
Application: risk to lifeline systems

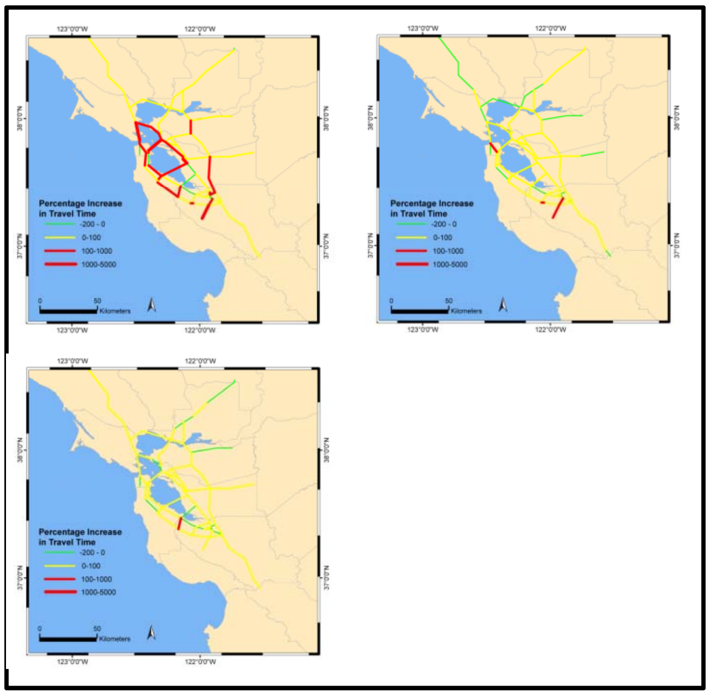


If we aggregate all these disruptions, we can compute a rate of disruption exceedance



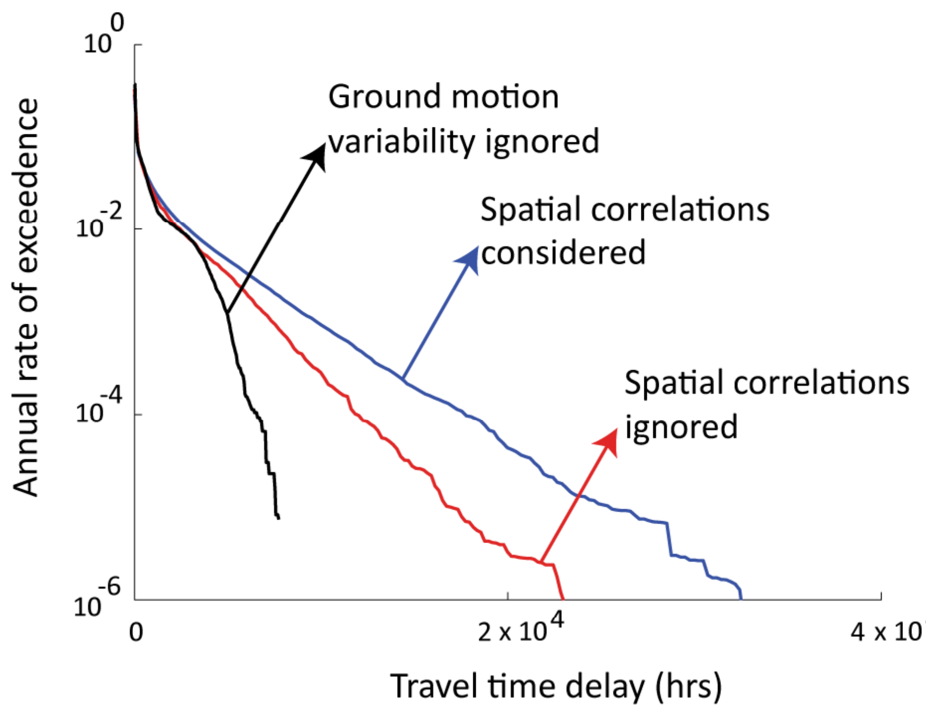
Consideration of correlations has a significant impact here



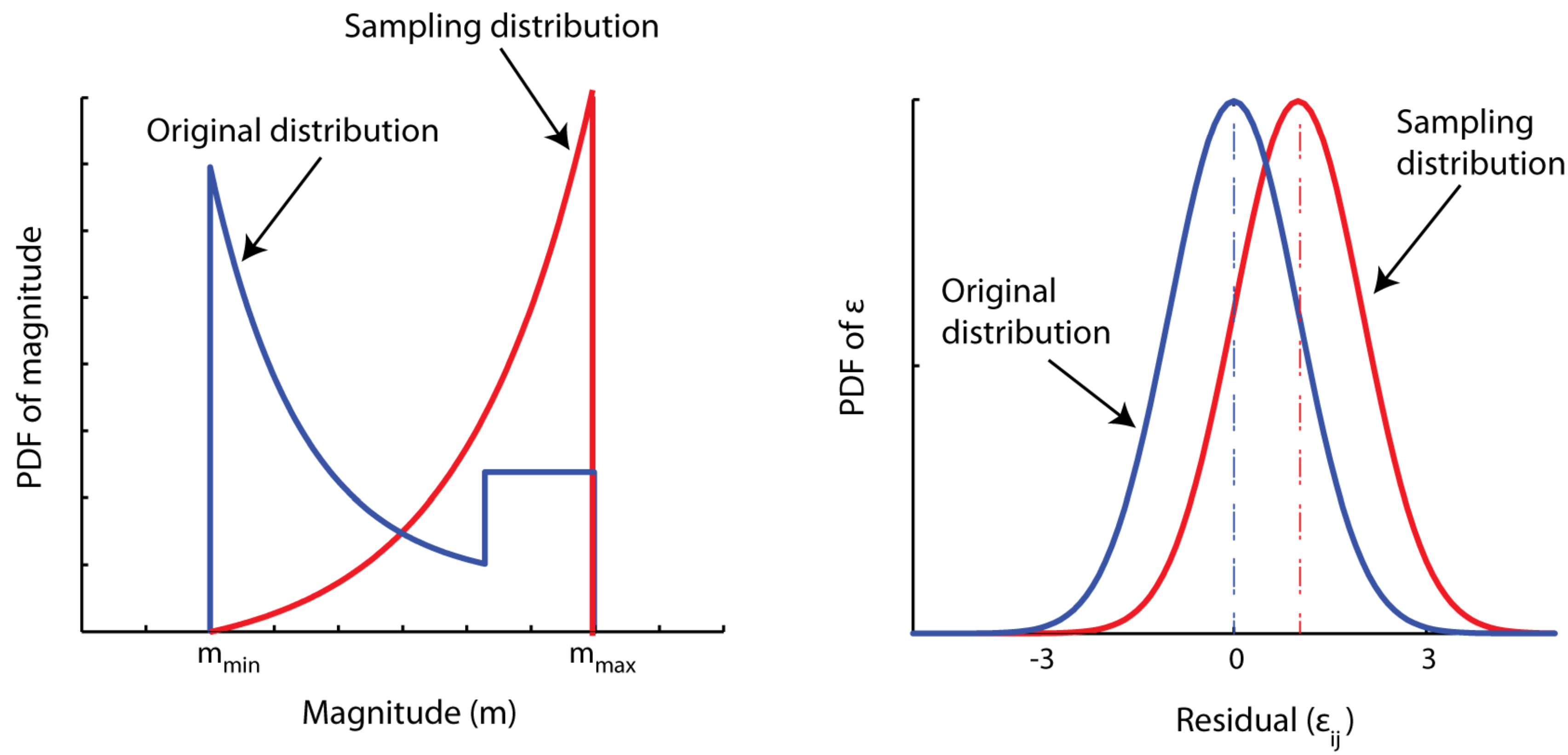


We can repeat this exercise omitting the ε correlation, to see the impact of this correlation

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \varepsilon_i + \eta$$

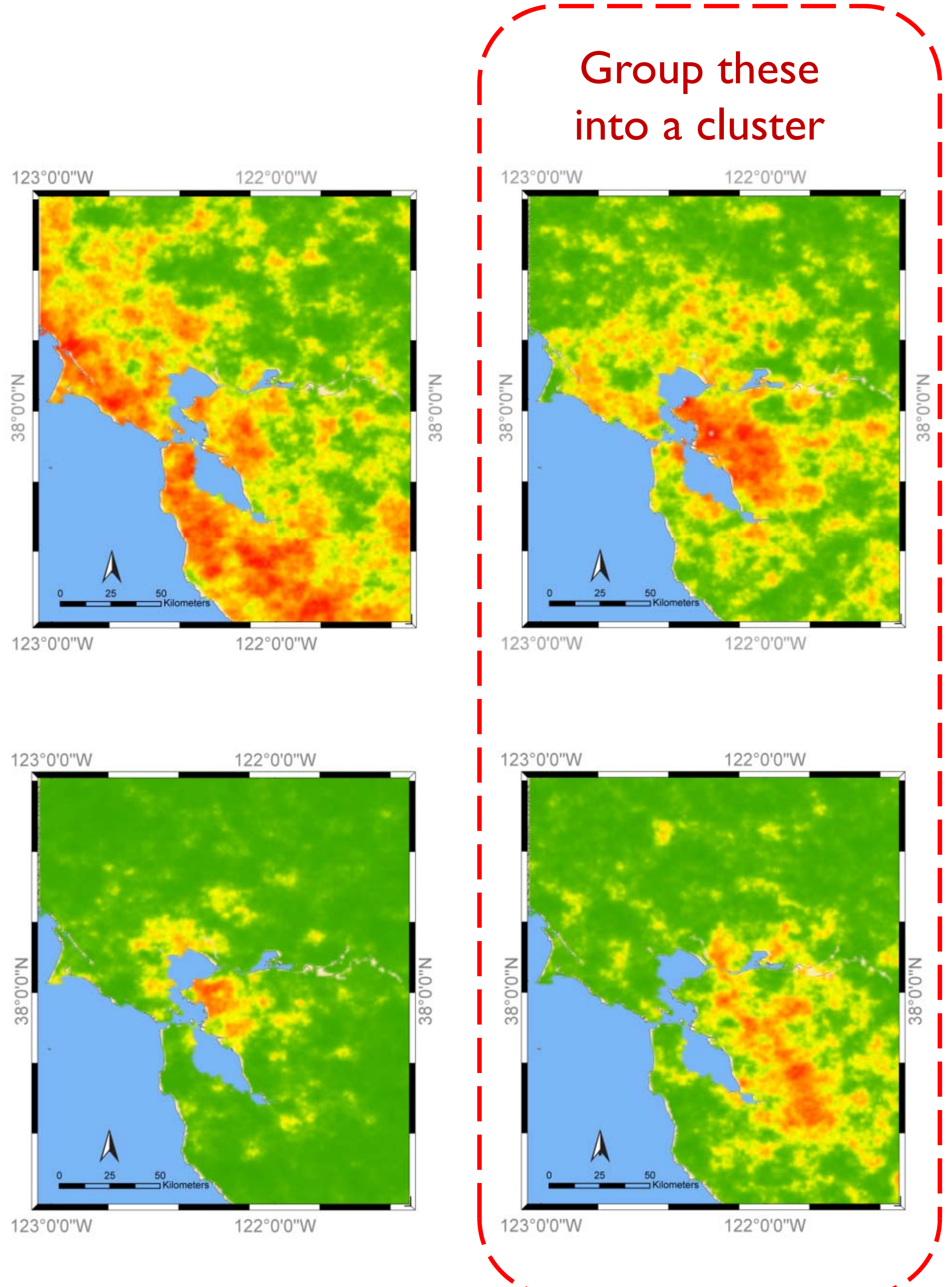


Improving simulation efficiency: importance sampling



If done correctly, this reduces our computational expense by ~2 orders of magnitude

Improving simulation efficiency: K-means clustering

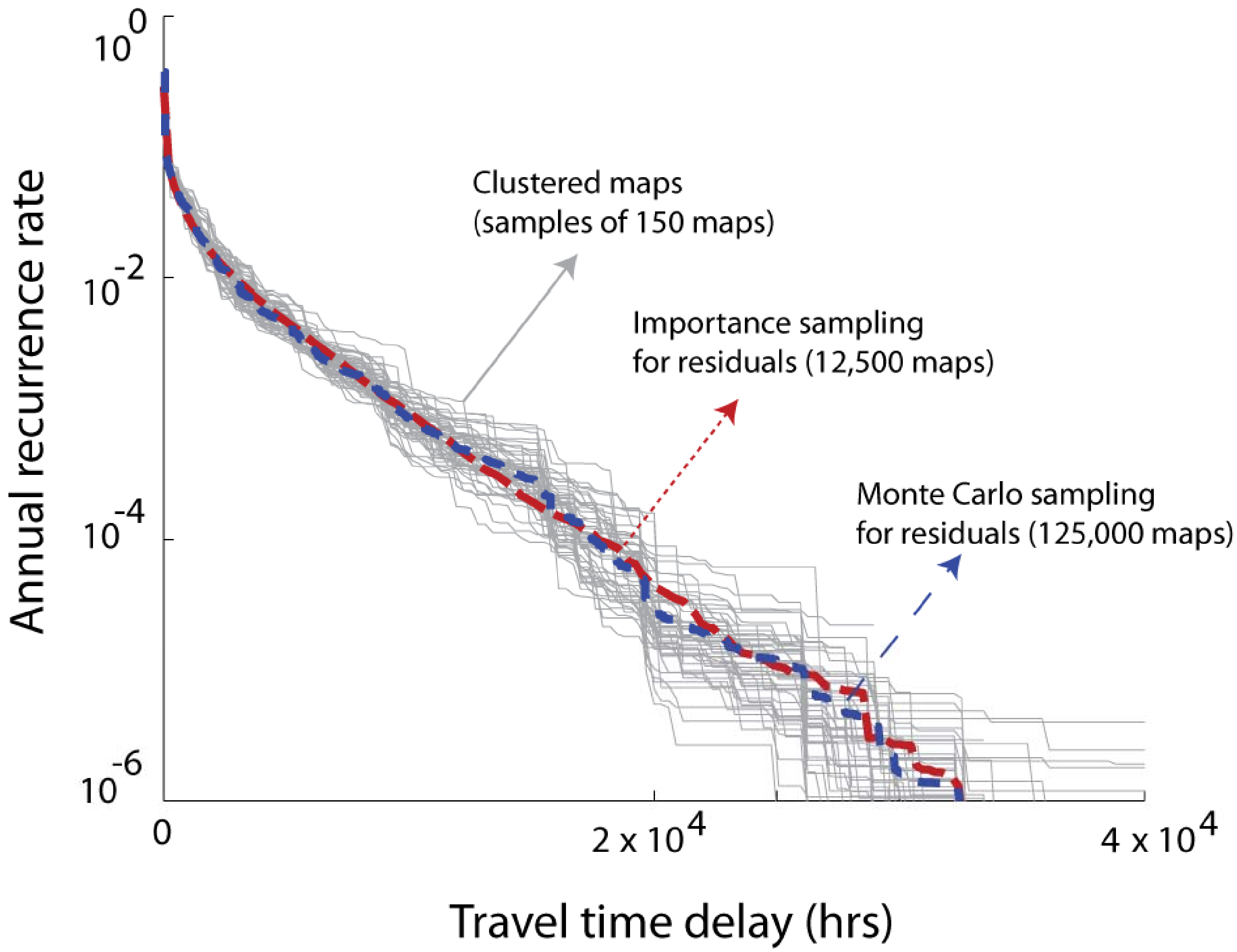


Select a *single* representative from the cluster to represent *all* simulations in the cluster

This can reduce computational expense by another ~2 orders of magnitude

Loss estimation using more efficient techniques

These techniques reduce our computational expense without biasing our estimates of disruption



Conclusions and current status

- We have used well-recorded earthquakes to measure spatial correlation of spectral acceleration values
- Using this model, we can generalize traditional PSHA to characterize ground motion intensities at many sites
- This characterization can not be done analytically, but efficient sampling and clustering make simulation tractable
- We assessed a simplified transportation network to demonstrate that this approach is unbiased with respect to basic Monte Carlo simulation
- We now hope to use this approach to study more realistic models distributed infrastructure