Spatial correlations in CyberShake ground motion simulations: Validation and estimation of non-stationarities

Jack W. Baker and Yilin Chen

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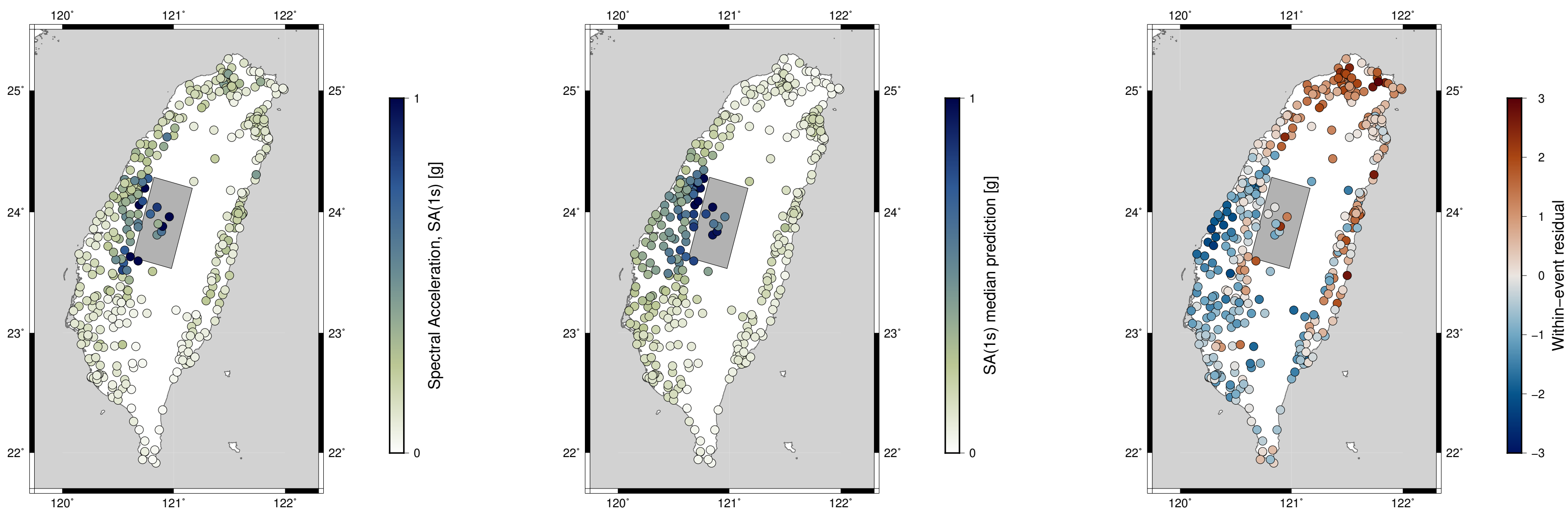
Spatial correlations in ground motion amplitudes

$$lnIM_{i,j} = \mu_{lnIM}\left(rup_i, site_j\right) + \delta B_i + \delta W_{i,j}$$

Observation Prediction(GMM) Between-event Residual **Within-event Residual**

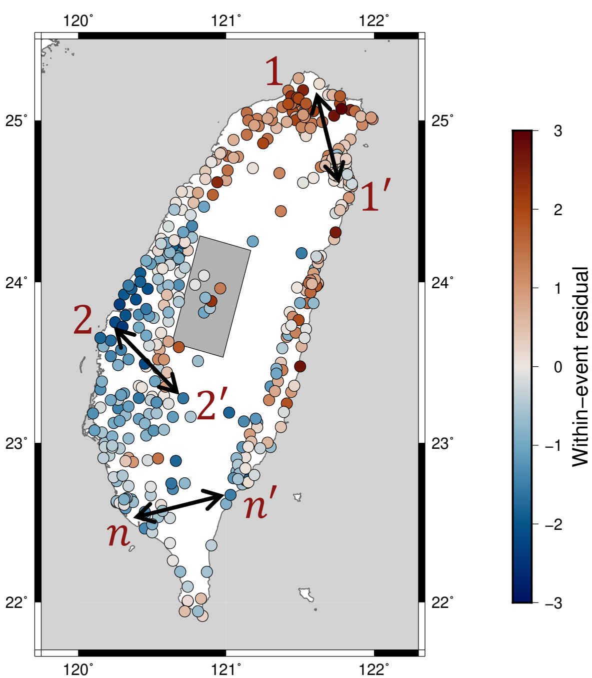


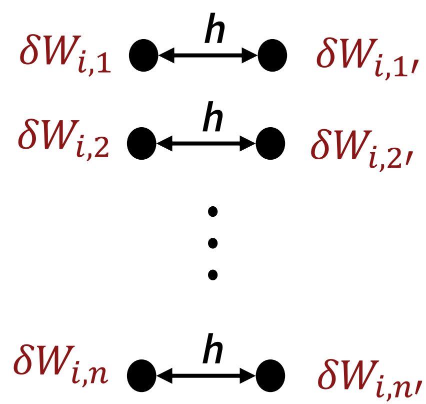
Figures from Baker, Bradley, Stafford (2021)

Baker and Chen

Empirically estimating correlations

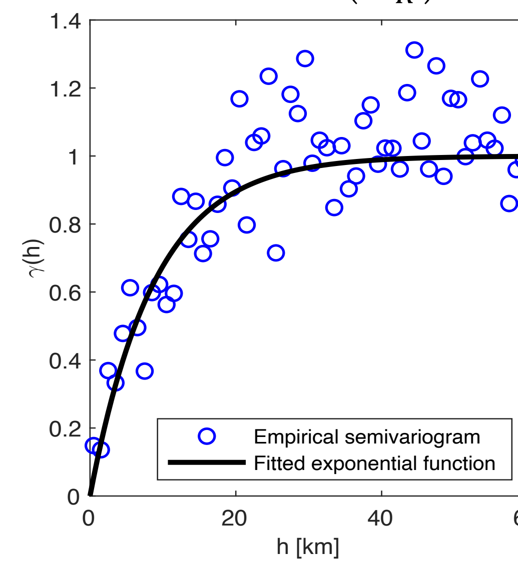
Assume sites with equal separation distance have equal correlation (“stationarity”)





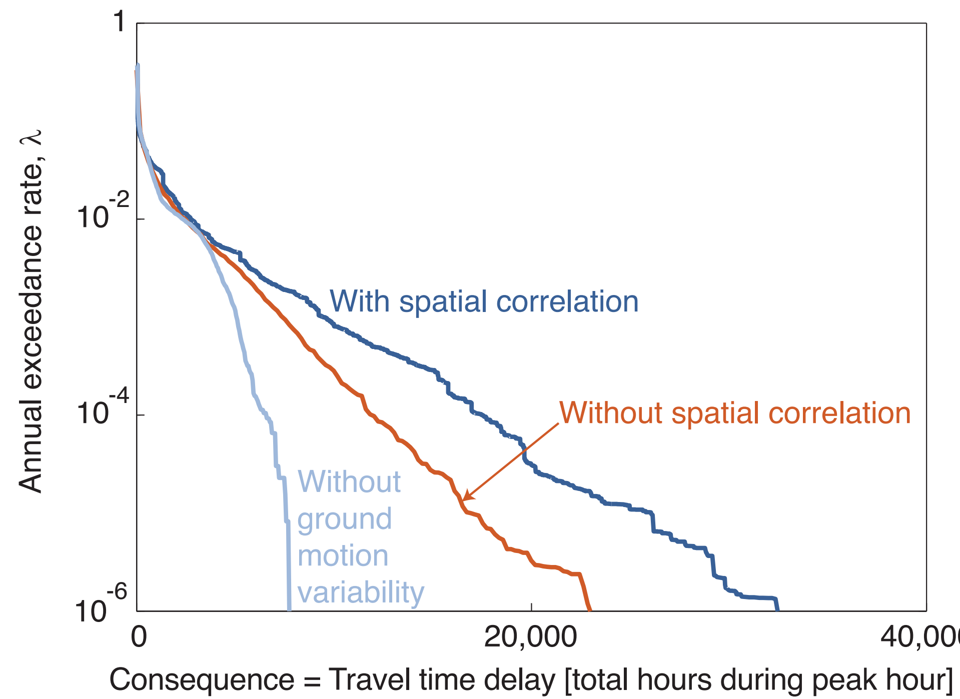
$$\gamma(h) = \frac{1}{2n}\sum_{j=1}^{n}\left[\delta W_{i,j} - \delta W_{i,j'}\right]^2$$

$$\tilde{\gamma}\,(h) = \mathrm{s}\left[1 - \exp\left(-\frac{3h}{R}\right)\right]$$



Impact of spatial correlations on risk

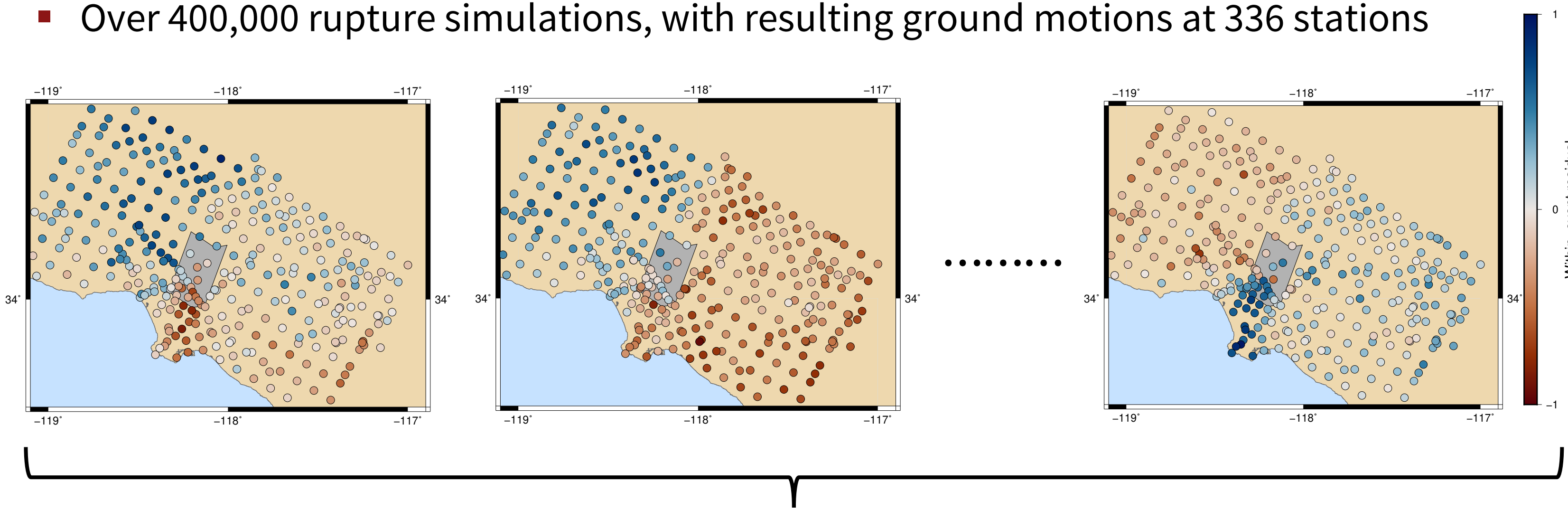
Spatial correlation is important for evaluating risk to distributed infrastructure systems.



Adapted from Jayaram and Baker (2010)

CyberShake simulations

- “Physics-based" simulations of wave propagation through a 3D crustal velocity model (v15.12)
- Earthquake ruptures are described kinematically by slip amplitude, direction, and timing across the fault
- Over 400,000 rupture simulations, with resulting ground motions at 336 stations

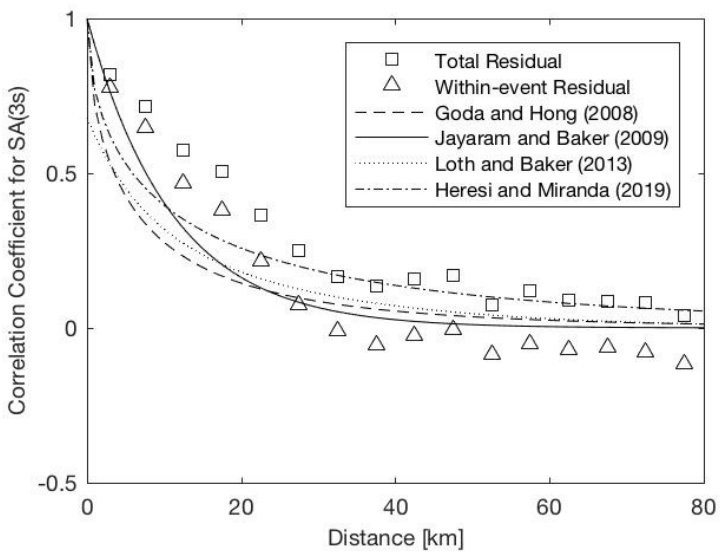


Multiple realizations of same rupture geometry

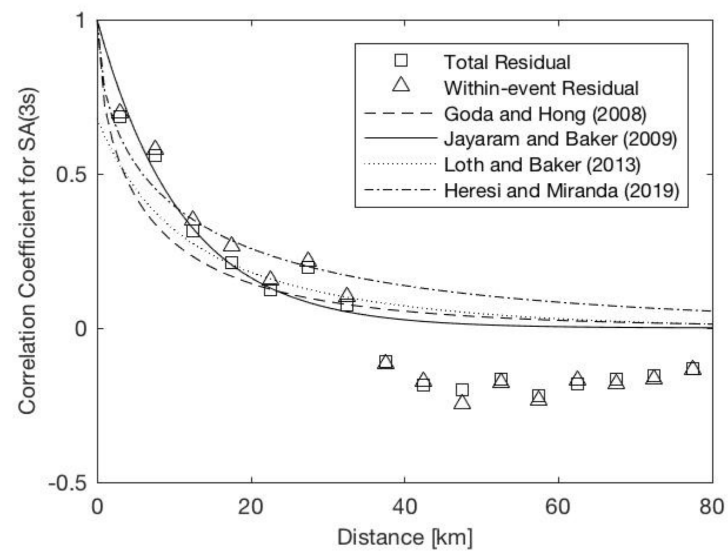
Chen and Baker (2019) *Bull. of the Seism. Soc. of Am.*

Stationary CyberShake correlations

San Andreas Ruptures

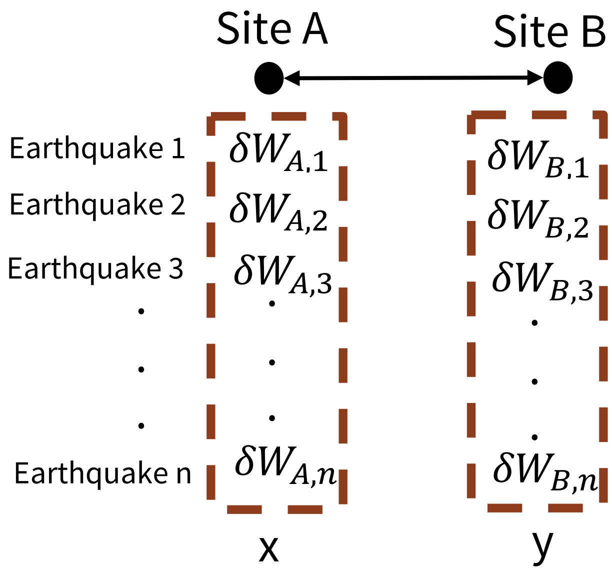


Puente Hills Ruptures

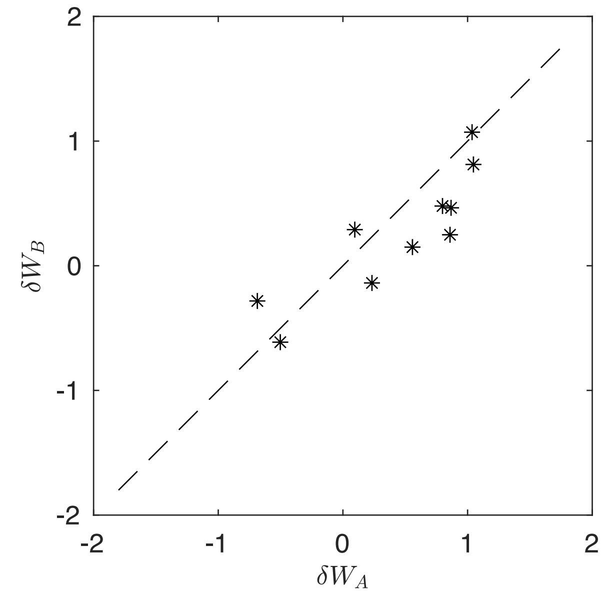


Site-specific correlation estimation using simulations

If we have many observations at a pair of interest

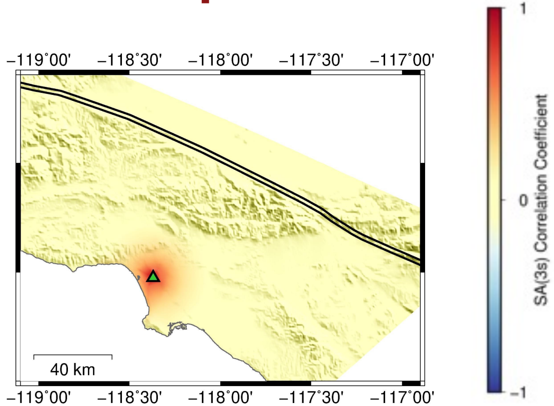


$$\rho_{AB} = \mathrm{corr}(x, y) = \frac{\sum_{i=1}^{n} (\delta W_{A,i} * \delta W_{B,i})}{\sqrt{\sum_{i=1}^{n} (\delta W_{A,i})^2}\sqrt{\sum_{i=1}^{n} (\delta W_{B,i})^2}}$$

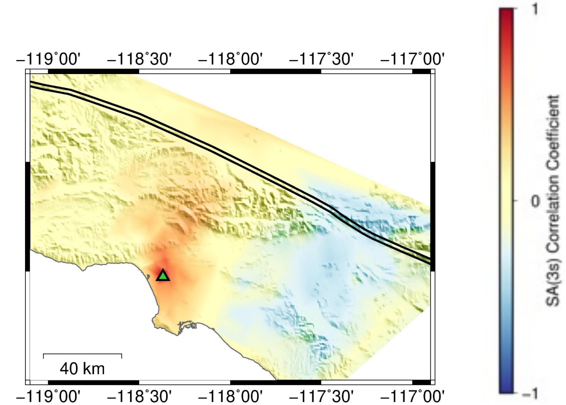


$$\hat{\rho} = 0.9$$

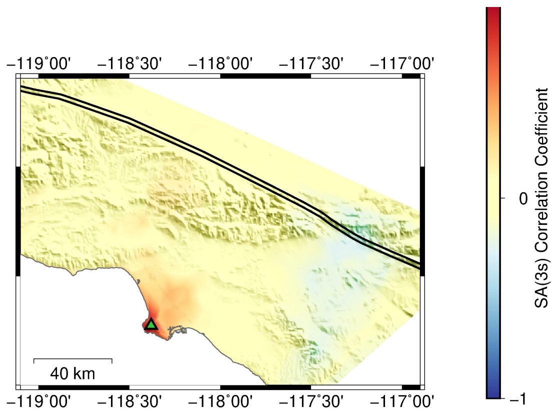
Observed pairwise correlations, for SA(3s)



Reference empirical model – stationary

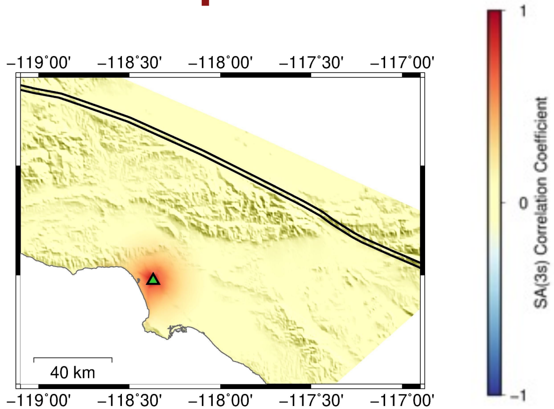


San Andreas M 8.05
reference site: s345

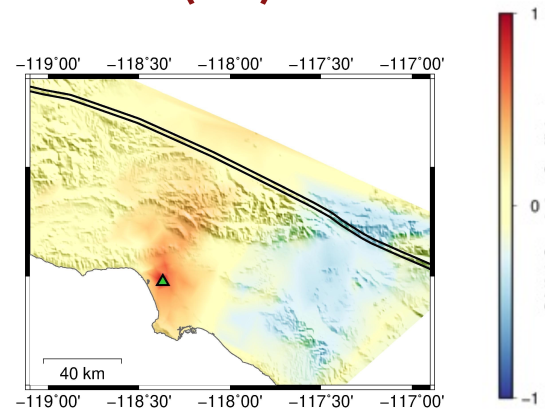


San Andreas M 8.05
reference site: s383

Observed pairwise correlations, for SA(3s)



Reference empirical model – stationary



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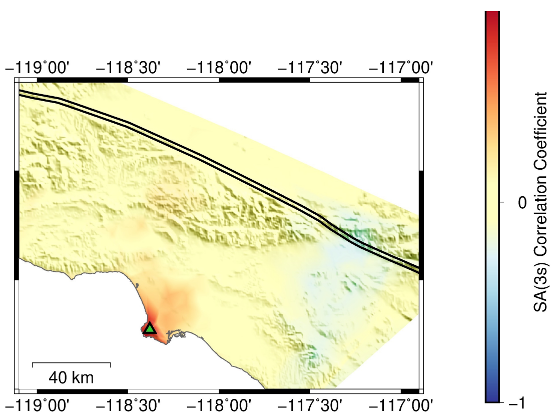

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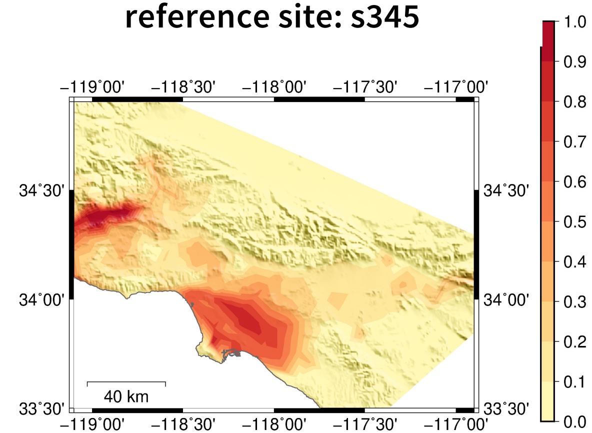
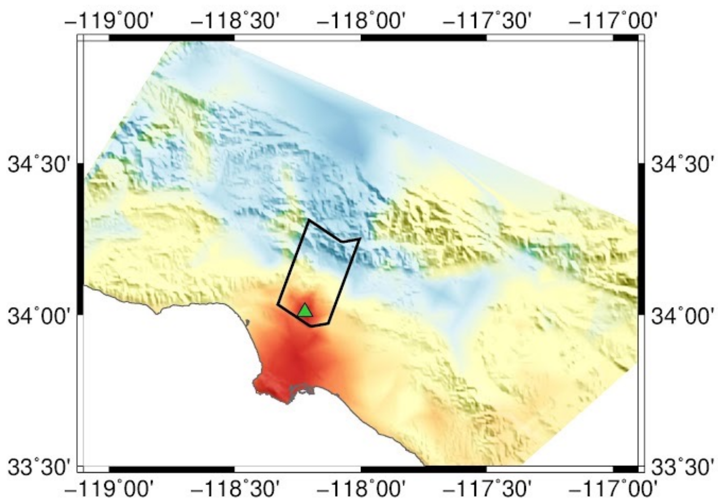
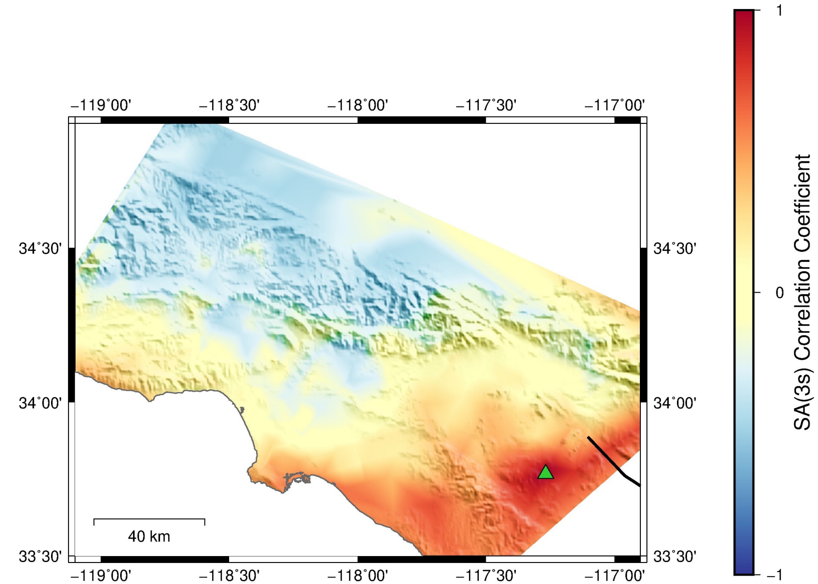


CyberShake region basin depth

Potential source effects

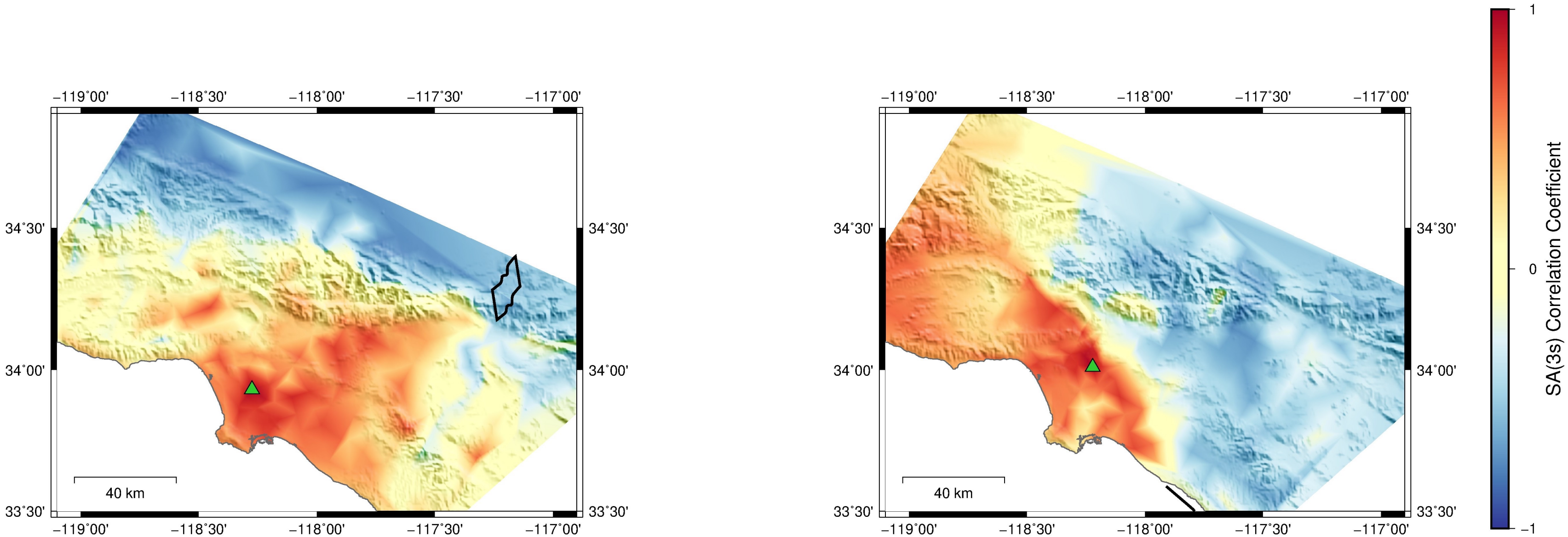


Puente Hills M 6.65
reference site: s389
T = 3s



San Jacinto M 6.95
reference site: s768
T = 3s

Potential path effects

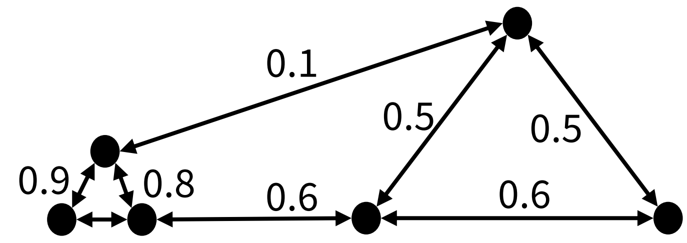


North Frontal M 6.55
reference site: s387
T = 3s

Newport M 6.55
reference site: s389
T = 3s

Can we identify areas with deviations from stationarity?

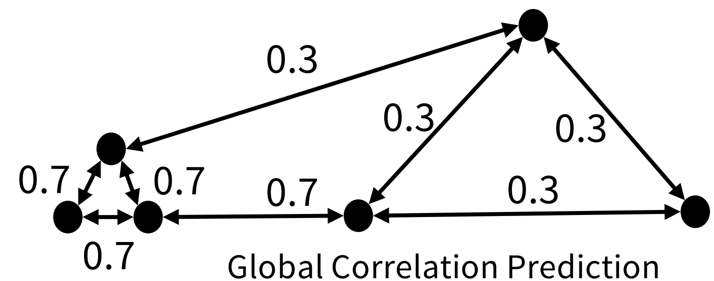
1. Construct a correlation graph



Correlation Graph

2. Fit a global correlation model

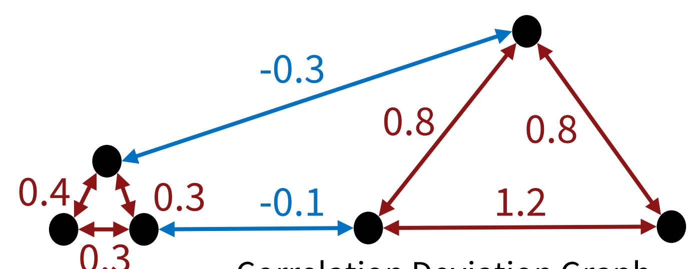
$$\hat{\rho}(i,j) = f(h(i,j))$$



Global Correlation Prediction

3. Calculate the deviation of each pair

$$A_{ij} = [Z(\rho(i,j)) - Z(\hat{\rho}(i,j))]\sqrt{n-3}$$



Correlation Deviation Graph

Chen and Baker (2021) *Computers and Geosciences*

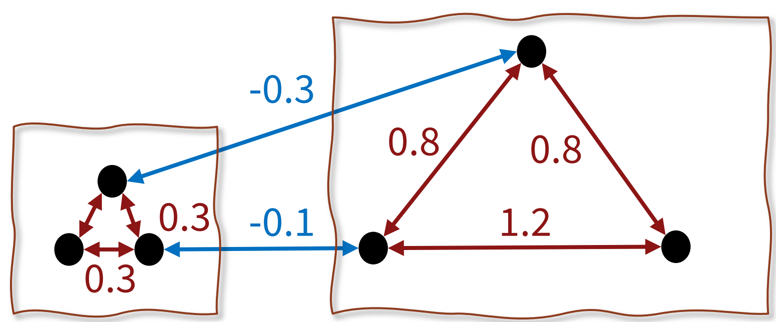
Signed Spectral Clustering to identify communities

Compute the signed degree matrix (absolute sum of edge weights connecting to node i)

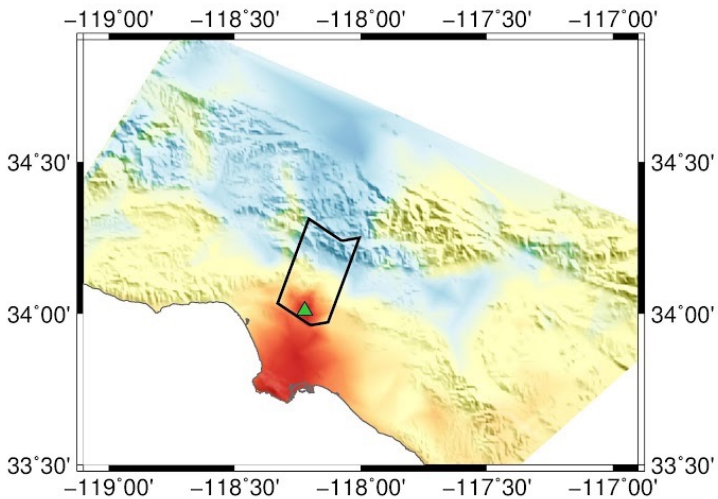
$$\tilde{D}_{ii} = \sum_i |A_{ij}|$$

Cluster based on eigenvectors of $\widetilde{D} - A$ (gives high within-cluster correlation and low across-cluster correlation)

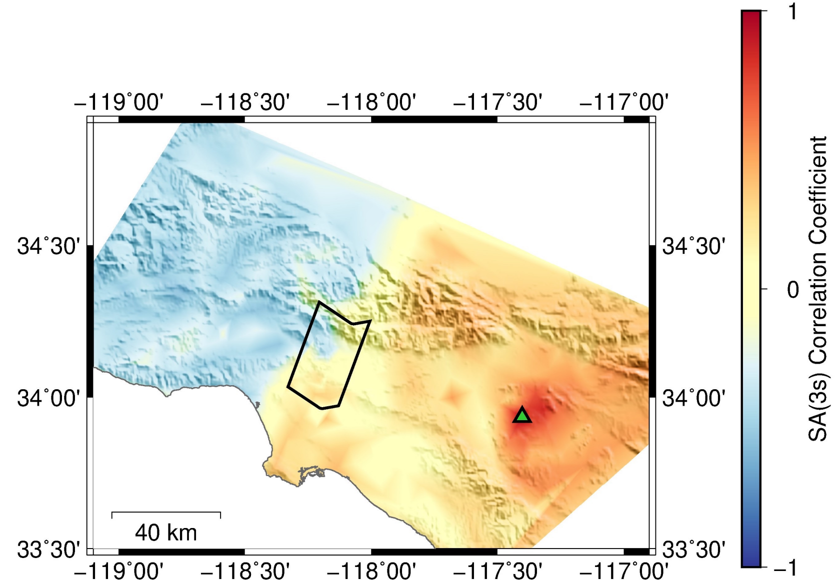
High-correlation communities



Application to CyberShake simulations

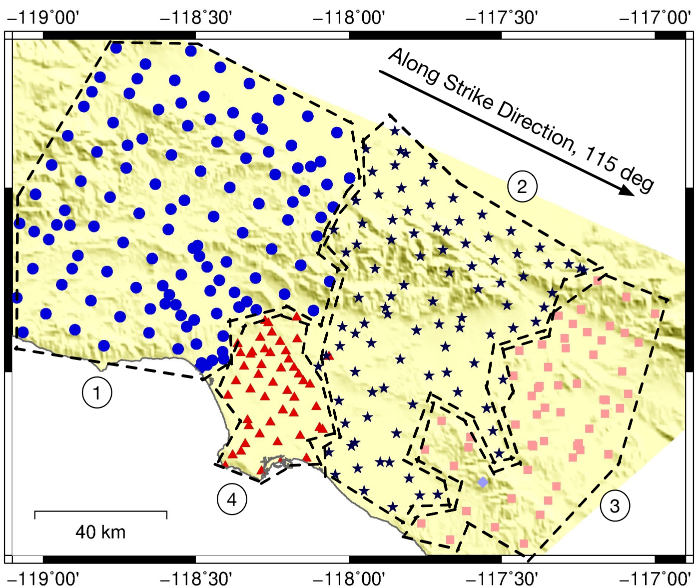


Puente Hills M 6.65
reference site: s389

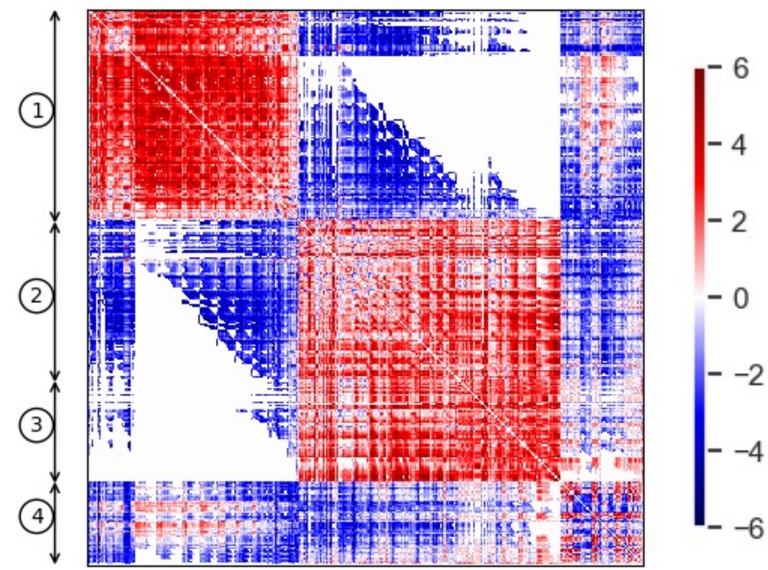


Puente Hills M 6.65
reference site: s684

Community detection results

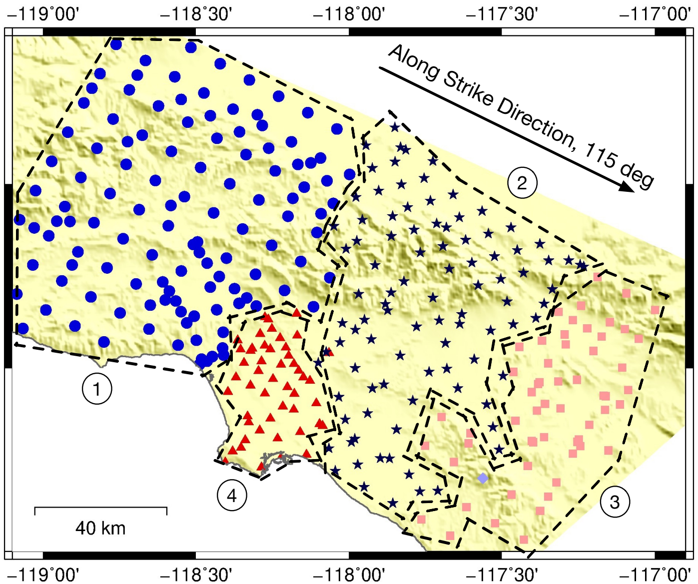


Detected communities

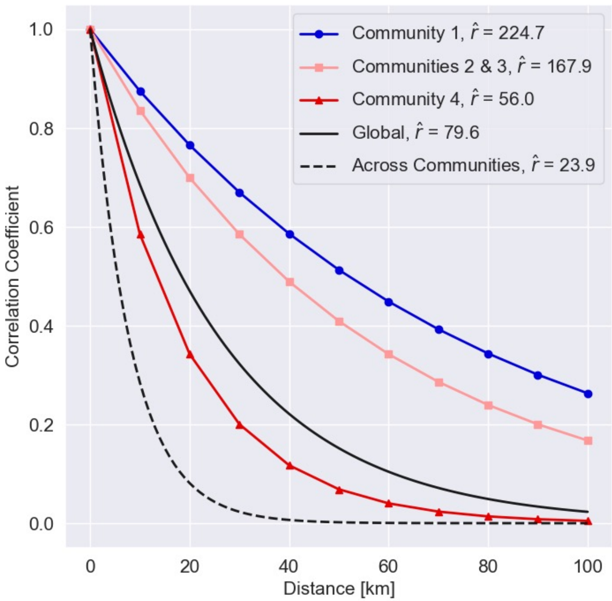


Edge weights between stations, grouped by community

Community-based correlation structure



Detected communities



Correlation model for each community

Conclusions

- Spatial correlations in amplitudes are an important characteristic in simulations, and a useful target for validation
- CyberShake stationary correlations appear to be consistent with empirical data at long periods
- Going further, repeated rupture simulations allow us to estimate pair-specific correlations, inferring causality and high-correlation communities of locations

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