# Spatial correlation in ground motion intensities: Measurement, prediction, and implications

Jack W. Baker

*Thanks to former students Lukas Bodenmann, Yilin Chen, Nirmal Jayaram, Christophe Loth, Maryia Markhvida, Mahalia Miller*

*Thanks to collaborators Brendon Bradley, Božidar Stojadinović, Eric Thompson, David Wald, Bruce Warden*

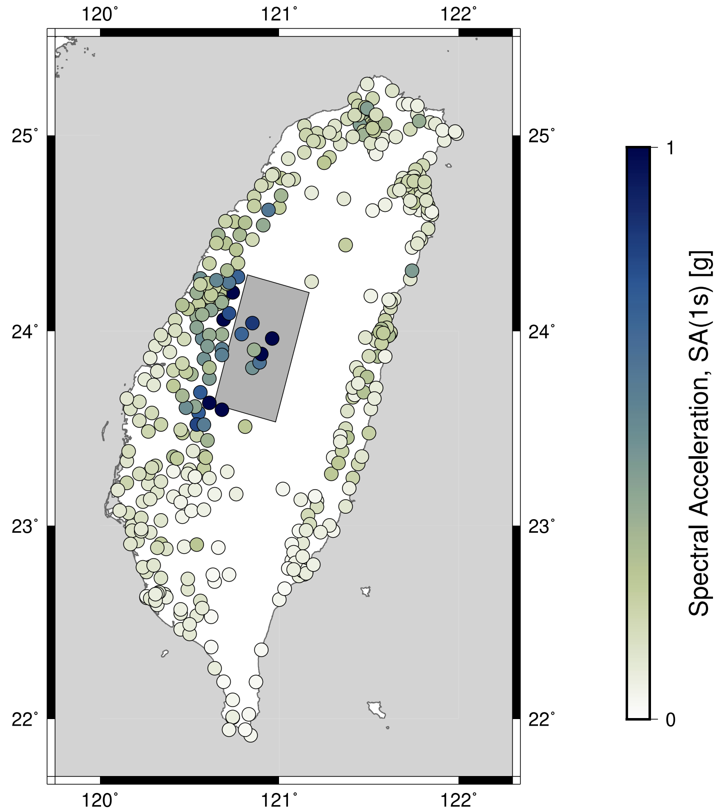
Stanford

School of Engineering &
Doerr School of Sustainability

# Thank you Dimitrios!

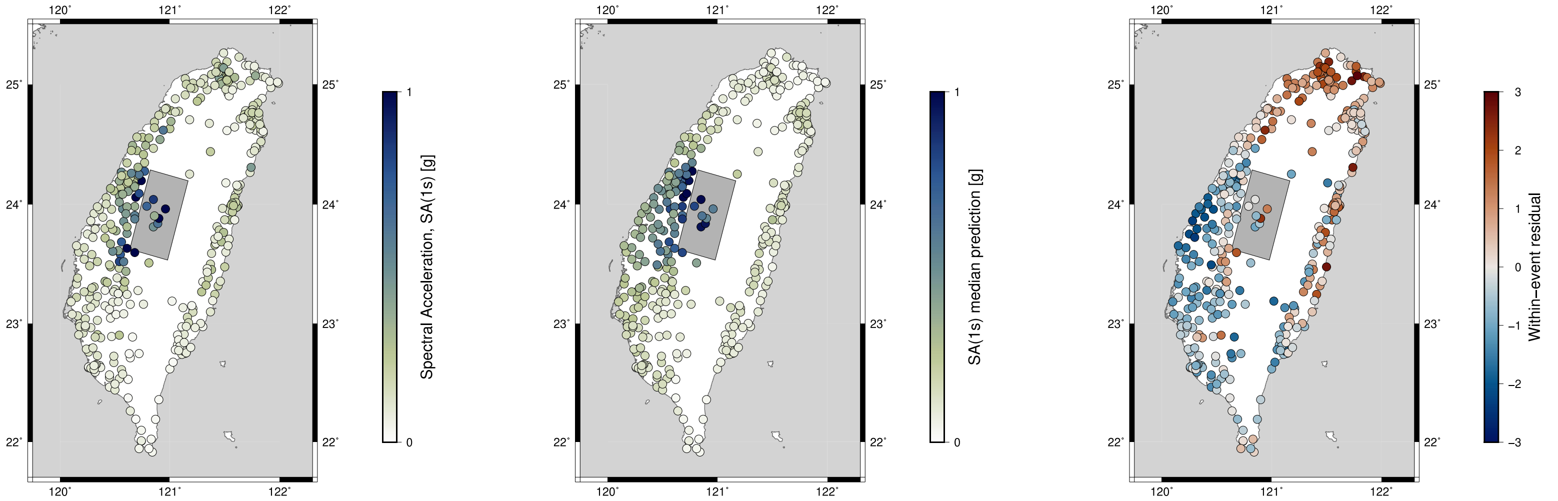
# Spatial correlations in ground motion intensity

Observed ground motions from the 1999 Chi-Chi earthquake



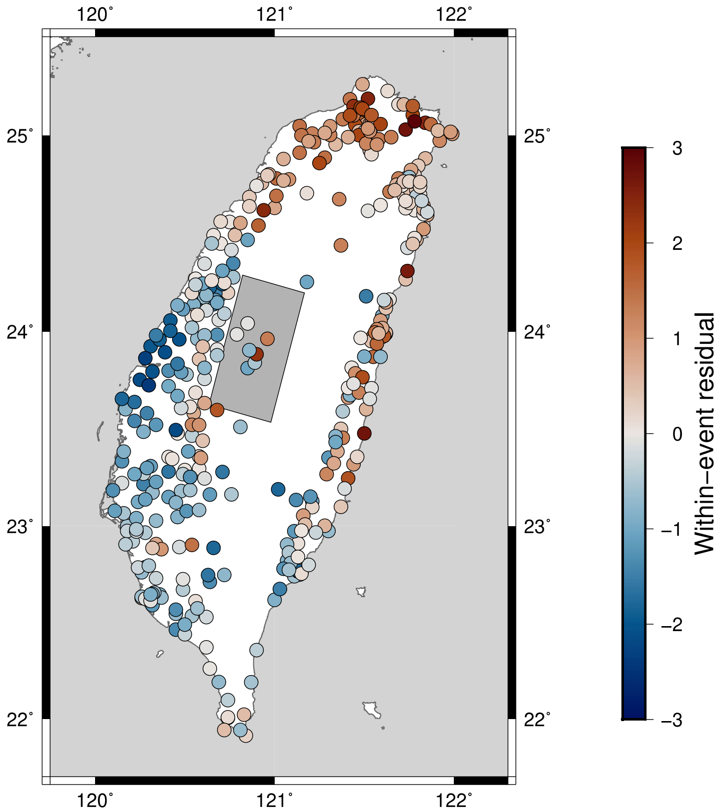
# Spatial correlation in ground motion

Observation = Prediction (Ground Motion Model) + **Within-event residual**

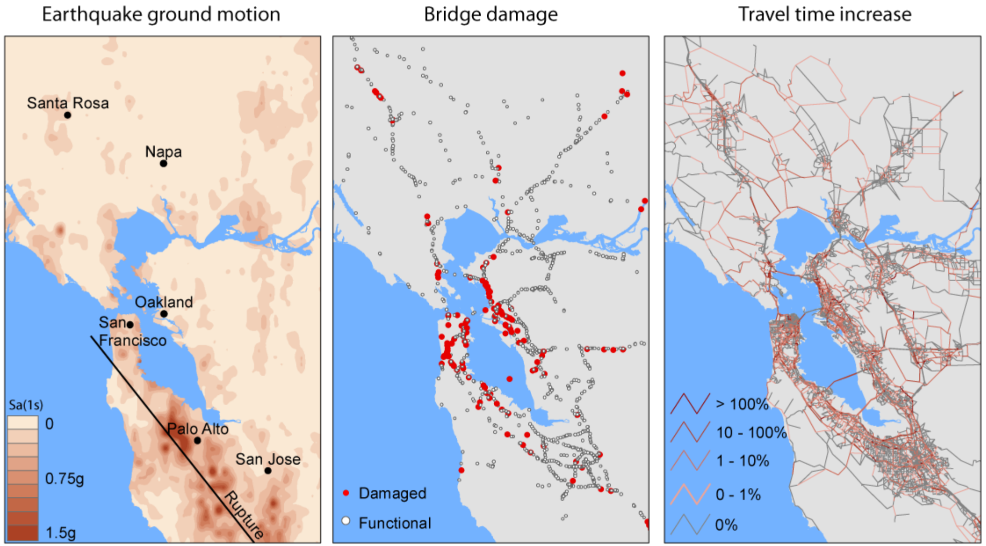


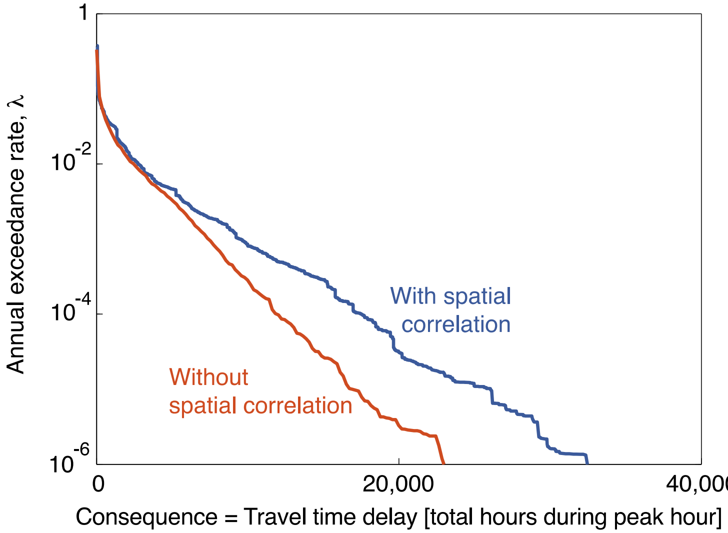
# Correlation results from several factors

- Similar wave propagation paths
- Similar local site effects
- Similar location to rupture asperities



# These correlations matter for regional risk simulation

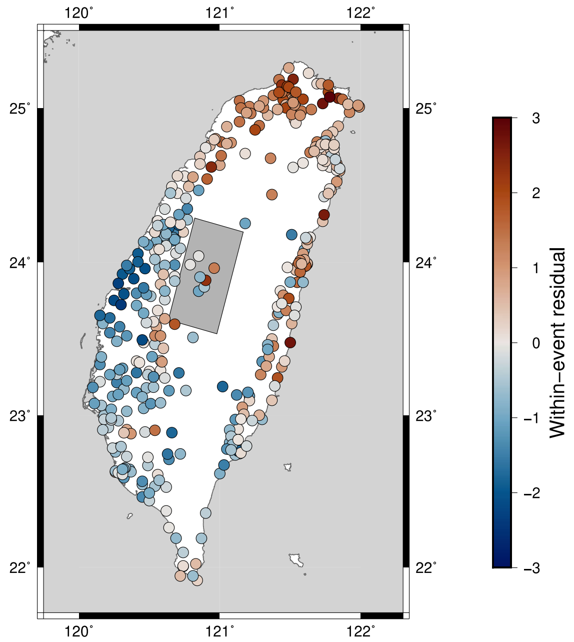



Jayaram and Baker (2010), Miller and Baker (2014)

# Estimation of spatial correlations

Ideally, we would like many observations for each station pair

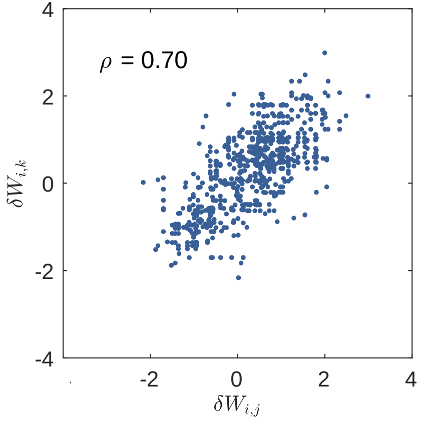



Baker, Bradley, Stafford (2021)

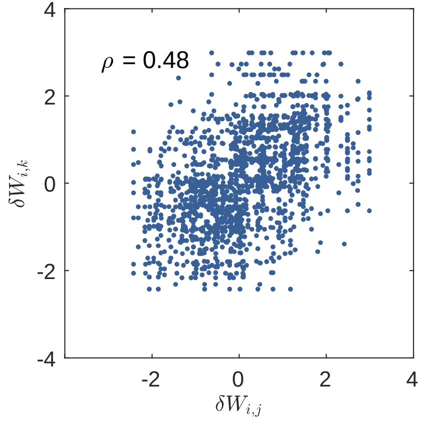
# Estimation of spatial correlations

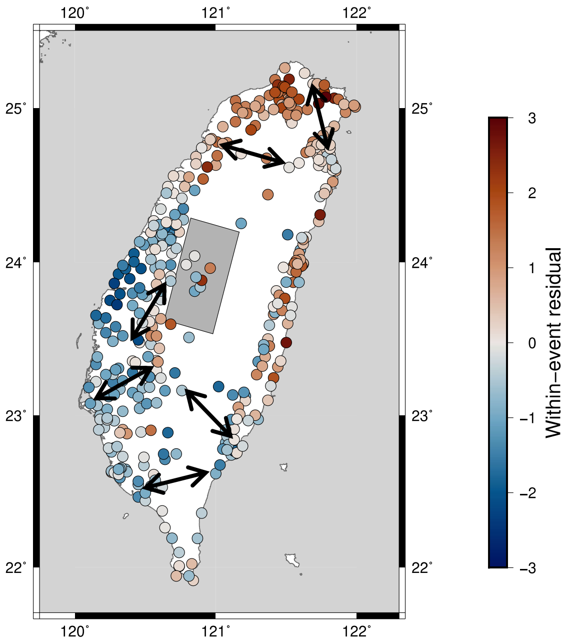
Typical practice: assume any pair of sites with equal separation distance has the same correlation (“stationarity”)

0-3km separation



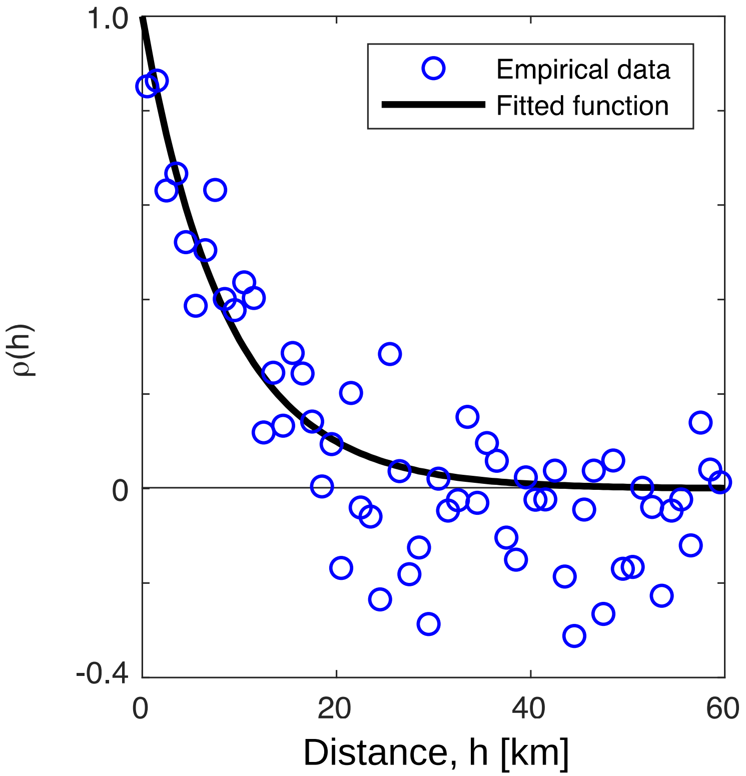

30-33km separation




Baker, Bradley, Stafford (2021)

# Estimation of spatial correlations




$$\rho_T = e^{-(c_1/h)^{c_2}}$$

“Traditional” models

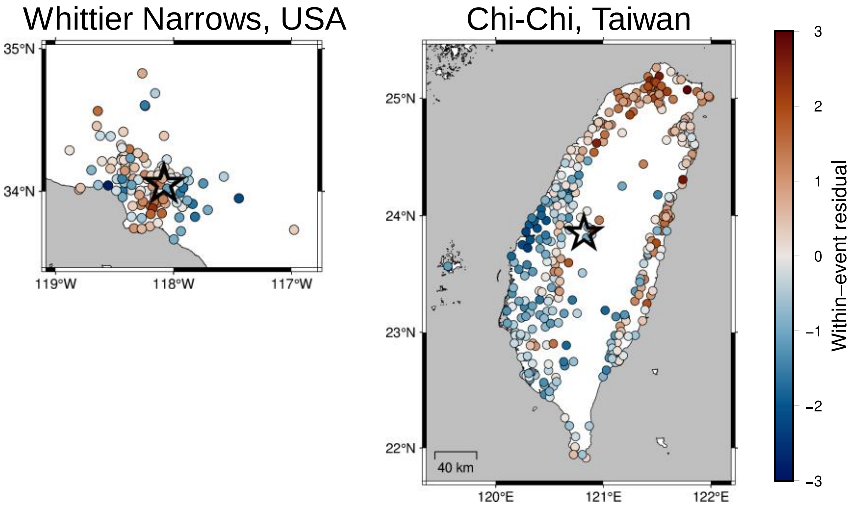
That’s the basic story, but it misses some complexities…

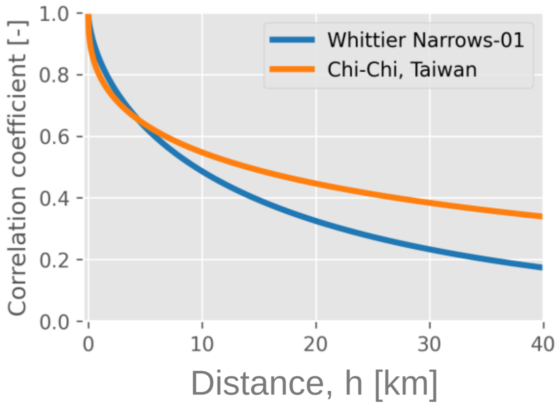
# Event-specific correlations, or something else?

Many studies have reported event-to-event variations

Hypothesized explanations:

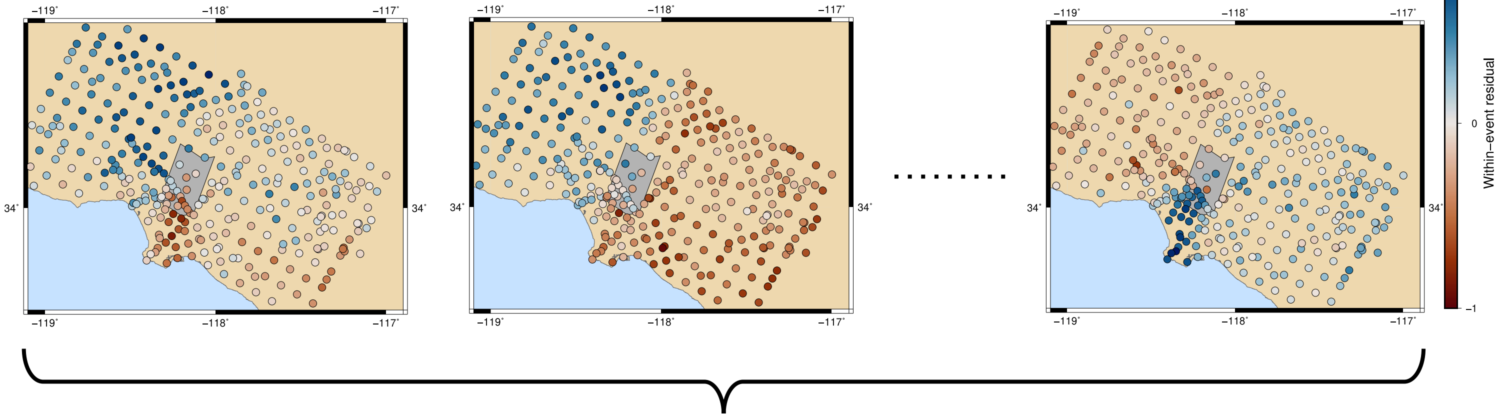
- Regional variations
- Magnitude dependence
- Site conditions
- Event-specific variability



# One path forward: study “physics-based” simulations

- We used CyberShake simulations (Graves et al. 2011) based on wave propagation through a 3D crustal velocity model
- Earthquake ruptures are described kinematically by slip amplitude, direction, and timing across the fault, and multiple realizations are available
- We find evidence of higher correlations in station pairs sharing a wave propagation path or similar geological conditions



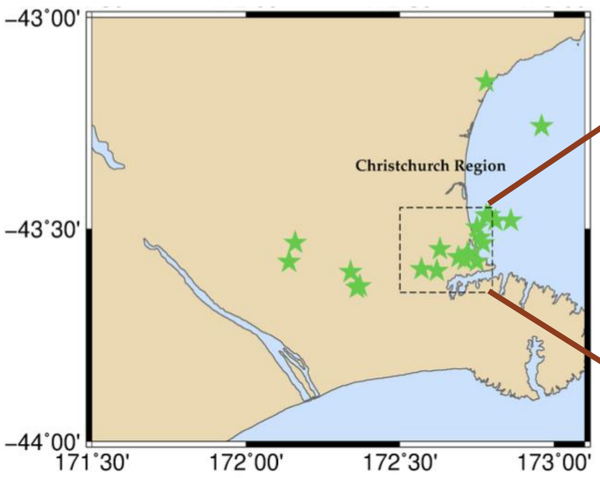

Multiple realizations of same rupture geometry

Chen and Baker (2019)

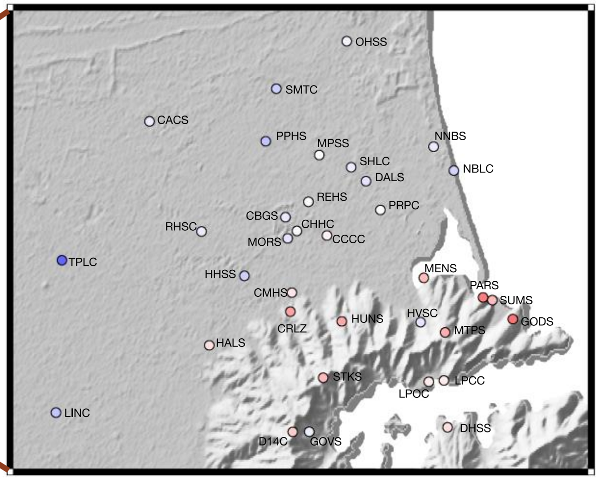
# A second path forward: Stations with repeated observations

## Christchurch, New Zealand

25 notable earthquakes

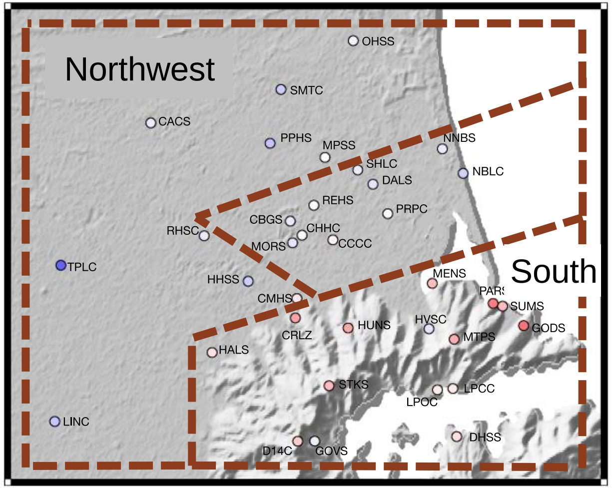



26 ground motion instruments

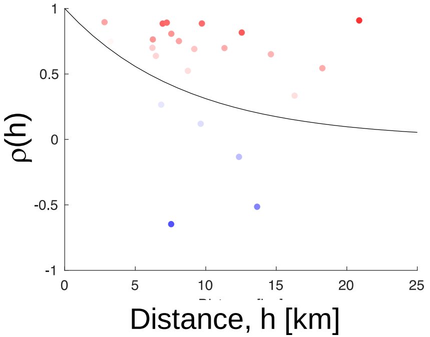


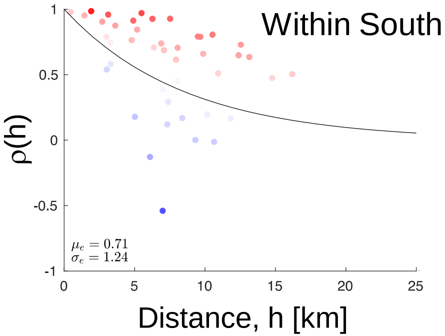

Chen, Bradley, Baker (2021)

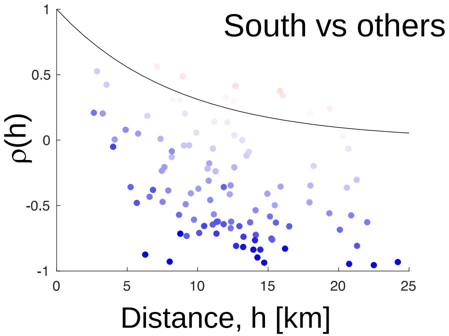
# Correlations are stronger within geologic regions




Christchurch site-specific residuals




Chen, Bradley, Baker (2021)

# A new predictive model: Consider extra geometry and soil condition variability

Traditional models:

$$\rho_{\mathrm{T}} = e^{-(c_1/h)^{c_2}}$$

New model:

$$\rho_N = \rho_T \cdot (c_3\,\rho_A + (1 - c_3)\rho_S)$$

$$e^{-(c_1/h)^{c_2}}$$

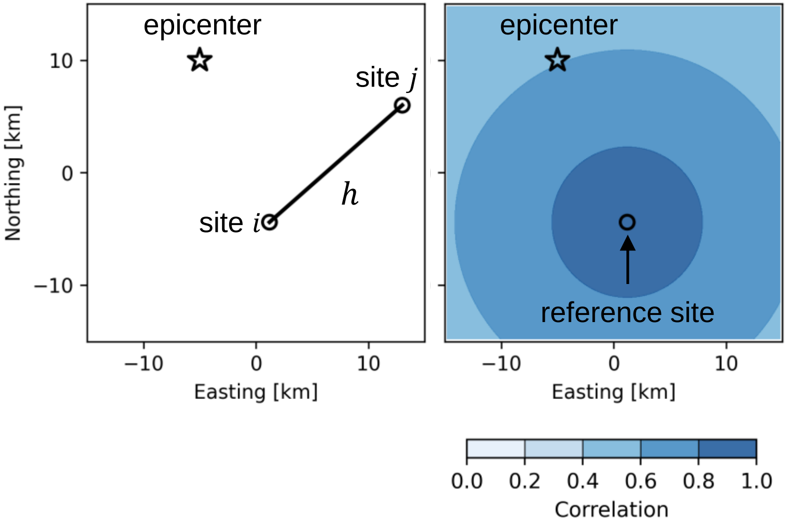
$$e^{-d_{\mathrm{S}}/c_5}$$

$$(1 + d_{\mathrm{A}}/c_4)(1 - d_{\mathrm{A}}/180)^{180/c_4}$$

# A new predictive model:
# Consider extra geometry and soil condition variability

$$\rho_N = \rho_T \cdot (c_3\, \rho_A + (1 - c_3)\rho_S)$$

$$e^{-(c_1/h)^{c_2}}$$

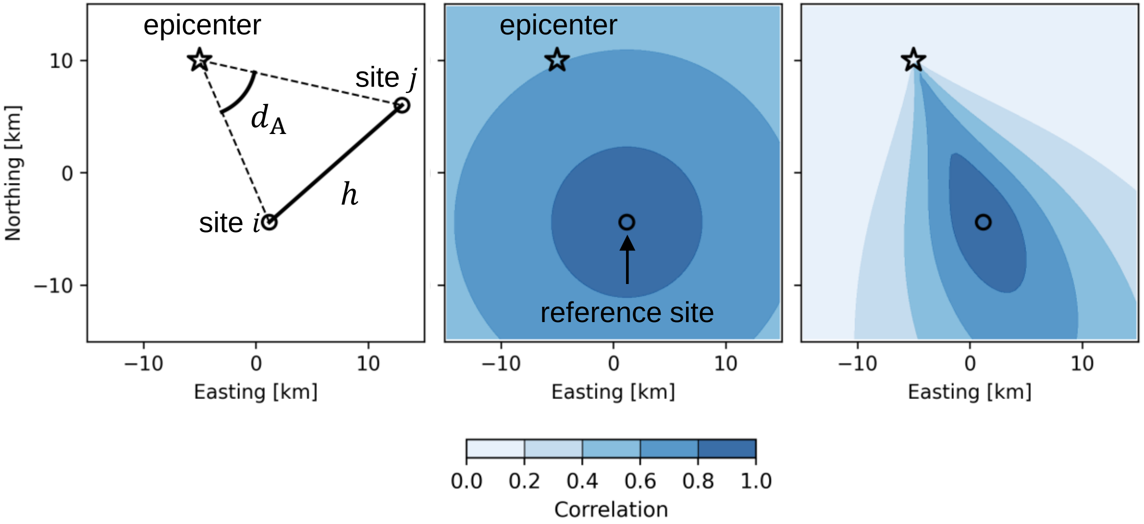



Bodenmann, Baker, Stojadinović (2023)

# A new predictive model:
# Consider extra geometry and soil condition variability

$$\rho_N = \rho_T \cdot (c_3\, \rho_A + (1 - c_3)\rho_S)$$

$$(1 + d_A/c_4)(1 - d_A/180)^{180/c_4}$$

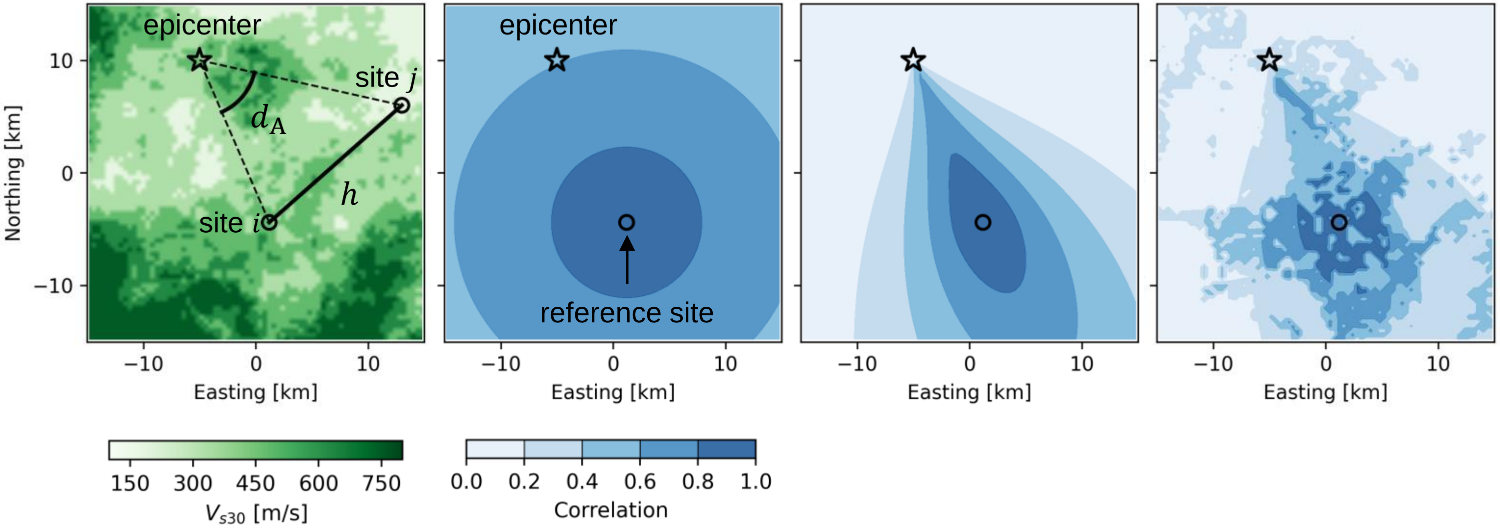


# A new predictive model: Consider extra geometry and soil condition variability

$$\rho_N = \rho_T \cdot (c_3\, \rho_A + (1 - c_3)\rho_S)$$

$$e^{-d_S/c_5}$$

$$d_S = |\, v_{s30,i} - v_{s30,j} \,|$$




We find that this model, fit to a global data set, is more predictive than fitting traditional models to individual earthquakes

Bodenmann, Baker, Stojadinović (2023)

# Predictive power versus model complexity

Traditional models (2003-):

$$\rho_{\mathrm{T}} = e^{-(c_1/h)^{c_2}}$$

Compare to ground motion models

Esteva and Rosenbluth (1964)

$$SA = c_1 + c_2 M - c_3 \ln R$$

# Predictive power versus model complexity

Traditional models:

$$\rho_{\mathrm{T}} = e^{-(c_1/h)^{c_2}}$$

New model:

$$\rho_N = \rho_T \cdot (c_3\, \rho_A + (1 - c_3)\rho_S)$$

$$e^{-(c_1/h)^{c_2}}$$

$$(1 + d_{\mathrm{A}}/c_4)(1 - d_{\mathrm{A}}/180)^{180/c_4}$$

$$e^{-d_{\mathrm{S}}/c_5}$$

Compare to ground motion models

Esteva and Rosenbluth (1964)

$$SA = c_1 + c_2 M - c_3 \ln R$$

Boore, Joyner, Fumal (1997)

$$\mu_{\ln SA} = c_0 + c_1\,(M-6) + c_2\,(M-6)^2 + c_3 \ln\left(\sqrt{R^2 + {c_4}^2}\right) + c_5 \ln(V_{S,30})$$

# Predictive power versus model complexity

Traditional models:

$$\rho_{\mathrm{T}} = e^{-(c_1/h)^{c_2}}$$

New model:

$$\rho_N = \rho_T \cdot (c_3\, \rho_A + (1 - c_3)\rho_S)$$

$$e^{-(c_1/h)^{c_2}}$$

$$e^{-d_{\mathrm{S}}/c_5}$$

$$(1 + d_{\mathrm{A}}/c_4)(1 - d_{\mathrm{A}}/180)^{180/c_4}$$

Compare to ground motion models

Esteva and Rosenbluth (1964)

$$SA = c_1 + c_2 M - c_3 \ln R$$

Boore, Joyner, Fumal (1997)

$$\mu_{\ln SA} = c_0 + c_1\,(M-6) + c_2\,(M-6)^2 + c_3 \ln\left(\sqrt{R^2 + {c_4}^2}\right) + c_5 \ln(V_{S,30})$$

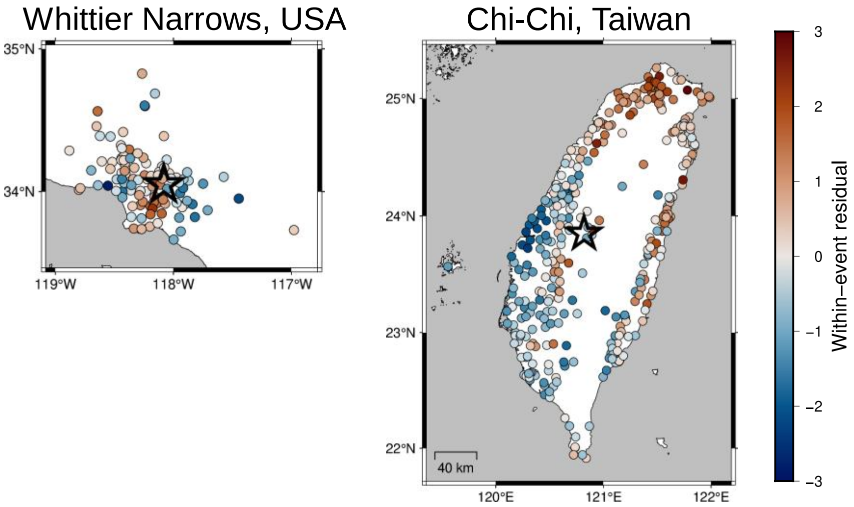
Chiou and Youngs (2014)

$$\begin{aligned}
\ln(y_{refij}) = {} & c_1 + \left\{c_{1a} + \frac{c_{1c}}{\cosh(2\cdot\max(\mathbf{M}_i - 4.5, 0))}\right\}F_{RVi} \\
& + \left\{c_{1b} + \frac{c_{1d}}{\cosh(2\cdot\max(\mathbf{M}_i - 4.5, 0))}\right\}F_{NMi} \\
& + \left\{c_7 + \frac{c_{7b}}{\cosh(2\cdot\max(\mathbf{M}_i - 4.5, 0))}\right\}\Delta Z_{TORi} \\
& + \left\{c_{11} + \frac{c_{11b}}{\cosh(2\cdot\max(\mathbf{M}_i - 4.5, 0))}\right\}(\cos\delta_i)^2 \\
& + c_2(\mathbf{M}_i - 6) + \frac{c_2 - c_3}{c_n}\ln(1 + e^{c_n(c_M - \mathbf{M}_i)}) \\
& + c_4 \ln(R_{RUPij} + c_5 \cosh(c_6\cdot\max(\mathbf{M}_i - c_{HM}, 0))) \\
& + (c_{4a} - c_4)\ln\left(\sqrt{R_{RUPij}^2 + c_{RB}^2}\right) \\
& + \left\{c_{\gamma1} + \frac{c_{\gamma2}}{\cosh(\max(\mathbf{M}_i - c_{\gamma3}, 0))}\right\}R_{RUPij} \\
& + c_8 \max\left(1 - \frac{\max(R_{RUPij} - 40, 0)}{30}, 0\right) \\
& \times \min\left(\frac{\max(\mathbf{M}_i - 5.5, 0)}{0.8}, 1\right)e^{-c_{8a}(\mathbf{M}_i - c_{8b})^2}\Delta DPP_{ij} \\
& + c_9 F_{HWij}\cos\delta_i\left\{c_{9a} + (1 - c_{9a})\tanh\left(\frac{R_{Xij}}{c_{9b}}\right)\right\}\left\{1 - \frac{\sqrt{R_{JBij}^2 + Z_{TORi}^2}}{R_{RUPij} + 1}\right\}
\end{aligned}$$

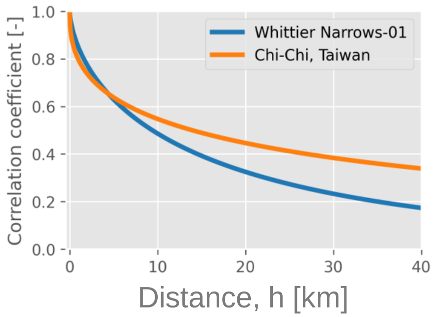
$$\begin{aligned}
\ln(y_{ij}) = {} & \ln(y_{ref_{ij}}) + \eta_i \\
& + \phi_1 \cdot \min\left(\ln\left(\frac{V_{S30j}}{1130}\right), 0\right) \\
& + \phi_2\left(e^{\phi_3(\min(V_{S30j}, 1130) - 360)} - e^{\phi_3(1130 - 360)}\right)\ln\left(\frac{y_{ref_{ij}}e^{\eta_i} + \phi_4}{\phi_4}\right) \\
& + \phi_5(1 - e^{-\Delta Z_{1.0j}/\phi_6}) \\
& + \varepsilon_{ij}
\end{aligned}$$

J. Baker

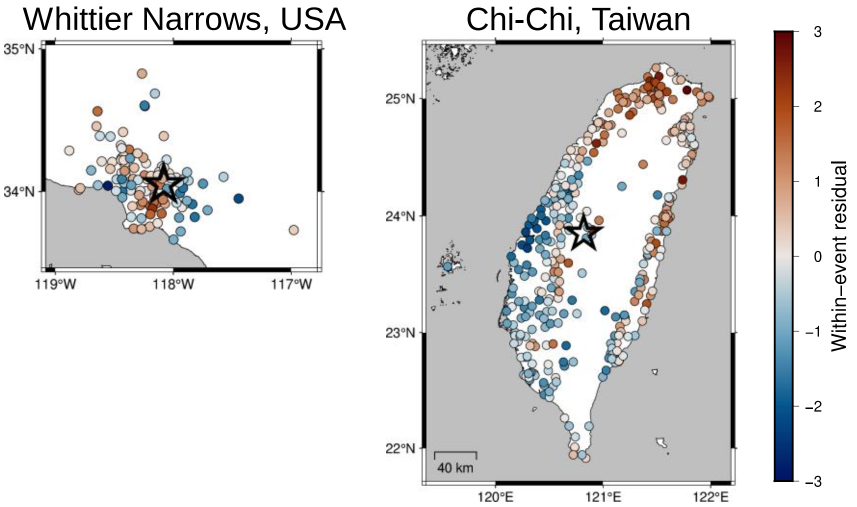
# Event-specific correlations, or something else?




Many studies have reported event-to-event variations



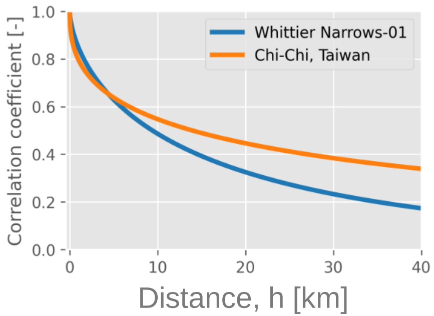
# Event-specific correlations, or something else?

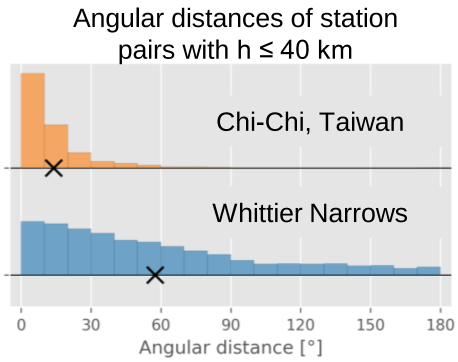



Many studies have reported event-to-event variations

Apparent explanations:

- Regional variations
- Magnitude dependence
- Source-to-site geometry
- Site conditions
- Event-specific variability



# Conclusions

Ground motions exhibit spatially correlated amplitudes,

*and*

these correlations have important practical impacts

Well-recorded earthquakes and ground motion simulations give us a means to measure these correlations and build predictive models

The next generation of correlation models will:

- Utilize numerical simulations plus observations
- Account for the effects of path, site, ?

*www.jackwbaker.com/joyner.htm*