# Validating Hybrid Broadband Ground-Motion Simulation of Moderate-Magnitude Active-Shallow-Crustal Earthquakes in New Zealand

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Te Whare Wānanga o Waitaha
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## 1. Introduction

Hybrid broadband ground-motion simulation offers significant advantages over conventional empirical ground-motion models. However, systematic validation against observations from historical events is essential to build confidence in its predictive capabilities and to identify where further improvement is needed. Previous validations studies have focused either on relatively large-magnitude earthquakes, for which finite-fault inversions are available (e.g., Pajaro et al., 2025a), or on small-magnitude events (3.5 ≤ **M** ≤ 5.0) for which the rupture can be represented by a point-source model (e.g., Lee et al., 2022). Comparatively little attention has being paid to moderate-magnitude events (5.0 ≤ **M** ≤ 7.0), which are too large to be represented as point sources yet too small for finite-fault models to be routinely available. This study addresses that gap by validating hybrid broadband ground-motion simulation for moderate-magnitude active-shallow-crustal earthquakes in New Zealand (NZ).

## 2. Ground-motion data

Figure 1 illustrates the location of the 78 events and 303 stations considered, yielding a dataset of 4,188 ground motions. Records were selected from the high-quality subset of the NZ Ground-Motion Database (NZGMDB, Pajaro et al., 2025b) v4.3 and further filtered using additional quality criteria to ensure a robust validation, including a minimum of three recordings per event and per station.

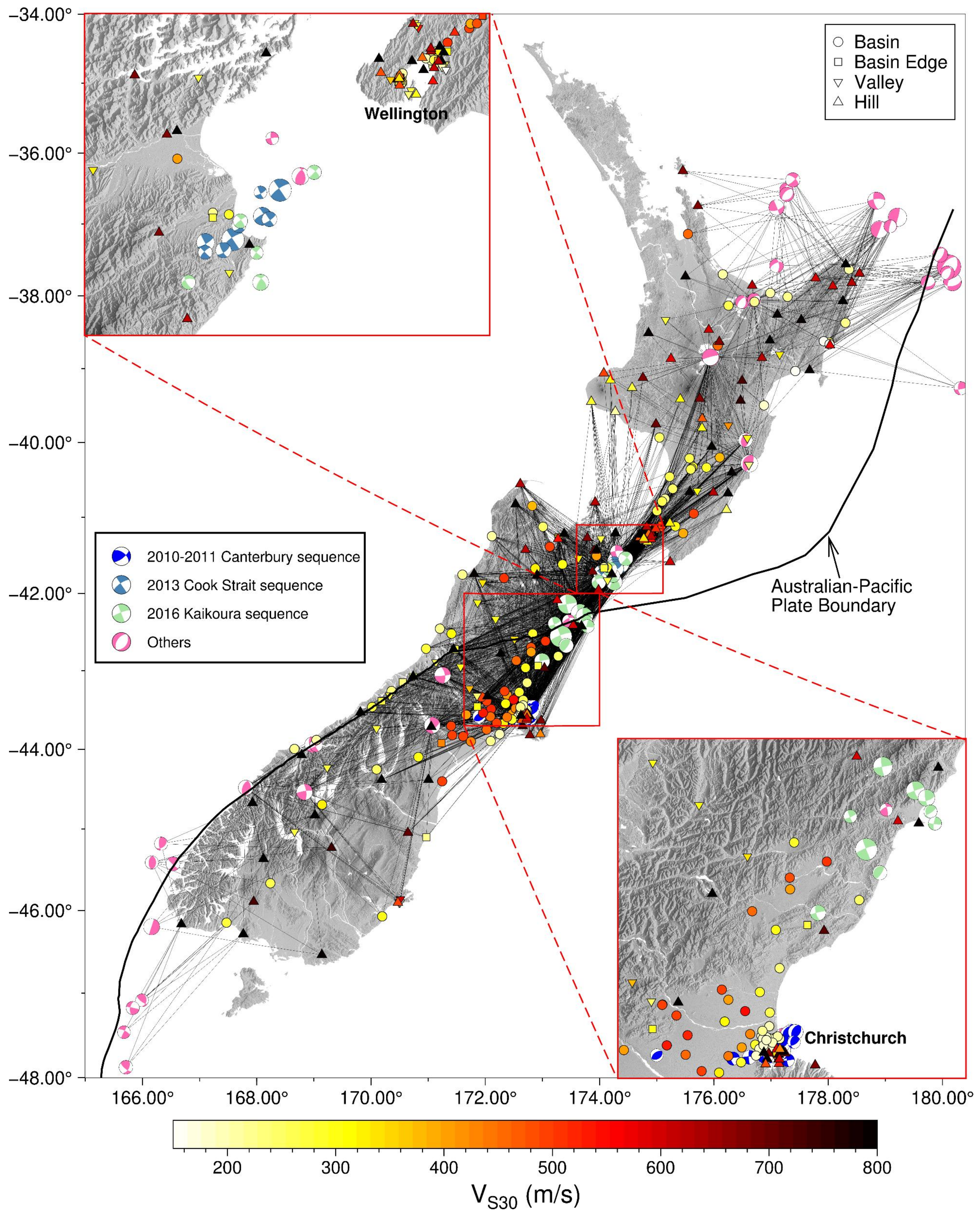


**Figure 1: Spatial distribution of the 78 earthquake sources and 303 stations used in the validation dataset across NZ.**

## 3. Methodology

Simulations are performed using the Graves and Pitarka (2010, 2015, 2016) hybrid broadband ground-motion simulation method, adopting a 100 m grid spacing, a minimum shear-wave velocity of 500 m/s, and a transition frequency of 1 Hz. The rupture plane is inferred from the event's Centroid Moment Tensor (CMT) solution together with magnitude-scaling relationships (Leonard, 2014).

Empirical ground-motion models typically used in NZ are adopted as a benchmark representing the conventional approach, with predictions generated for several intensity measures (IMs) of engineering interest.

The residual between observed and predicted IMs (from either method) is computed as

$$\Delta_{es} = \ln(IM_{obs}) - \ln(IM_{pred})$$

And mixed-effect regression is performed to decompose this residual into its components of ground-motion variability:

$$\Delta_{es} = a + \delta B_e + \delta S2S_s + \delta W_{es}^0$$

## 4. Model bias and total standard deviation

Figure 2 shows the overall model bias, $a$, and total standard deviation, $\sigma$, of the residuals across the full database. The bias results indicate that the simulations are more accurate than the empirical models for several IMs, including high-frequency effective amplitude spectra (EAS), short-period spectral acceleration (SA), and peak ground velocity (PGV). However, the simulations show a notable underprediction for EAS between 0.5-0.8 Hz and SA between 1.5-2.5 s. The standard deviation results show comparable precision between the two methods, with the empirical models giving slightly lower values for most IMs. $\sigma$ increases markedly at high frequencies for both methods, which explains the large standard deviation obtained for Arias intensity (AI), a parameter strongly correlated with high-frequency ground motion.

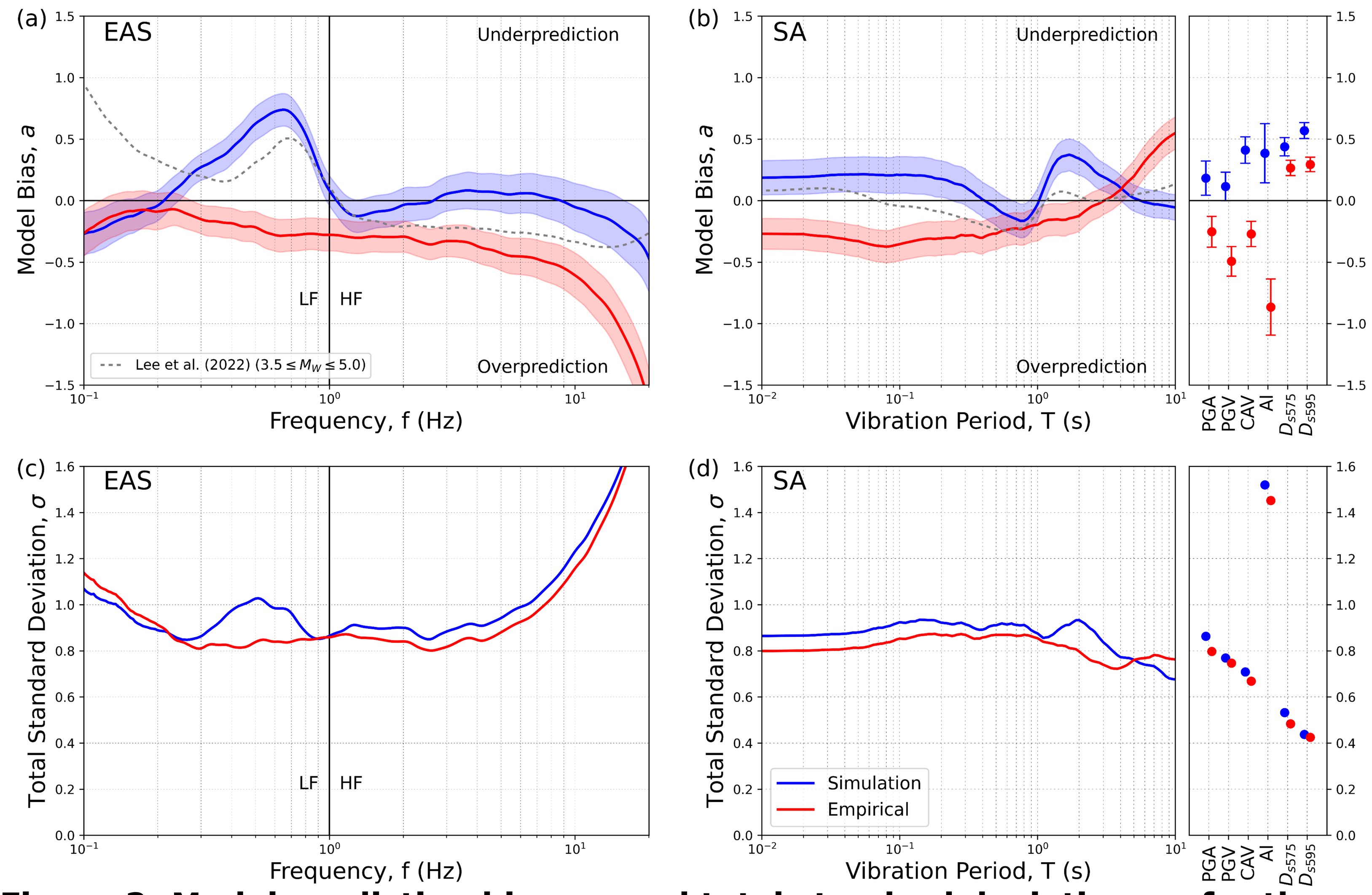


**Figure 2: Model prediction bias, $a$, and total standard deviation, $\sigma$, for the simulation and empirical predictions, for different intensity measures.**

## 5. Low-frequency underprediction

Figure 3 shows a correlation between the site-to-site residuals, $\delta S2S_s$, for EAS(0.5Hz) and the site period, $T_0$: sites with a period closer to 2 s (i.e., a site frequency near 0.5 Hz) tend to show more positive $\delta S2S_s$ values. This correlation is stronger for the simulations than for the empirical models, indicating that part of the simulations' underprediction steams from limitations in capturing site response and basin effects. This limitation is partially explained by the adopted 100 m grid spacing and minimum shear-wave velocity of 500 m/s.

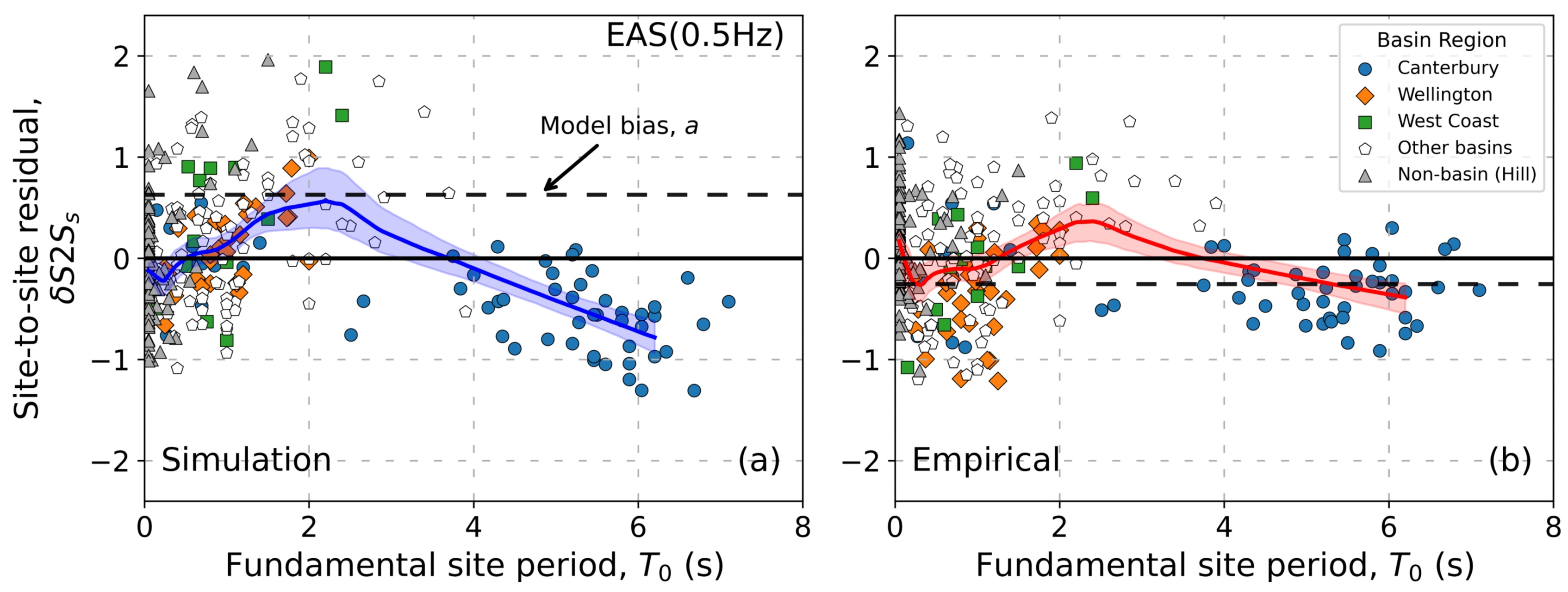


**Figure 3: Comparison of site-to-site residual, $\delta S2S_s$, for EAS(0.5Hz) vs. fundamental site period, $T_0$, for (a) the simulation and (b) empirical predictions.**

## 6. High-frequency increase in residual variability

Our simulations adopt a single value of the high-frequency attenuation parameter, $\kappa_0$=0.045 s, and the Brune stress parameter, $\Delta\sigma$=5 MPa, both of which strongly influence high-frequency (HF) ground motion. Figure 4 plots $\delta S2S_s$ for EAS(20Hz) against site-specific $\kappa_0$ values computed by Sepulveda et al. (2026), and $\delta B_e$ against event-specific $\Delta\sigma$ values computed by Zhu et al. (2022). The results show that using generic values explains a substantial share of the observed HF variability, suggesting that adopting spatially varying parameter values in future simulations could allow HF simulation precision to surpass that of empirical models.

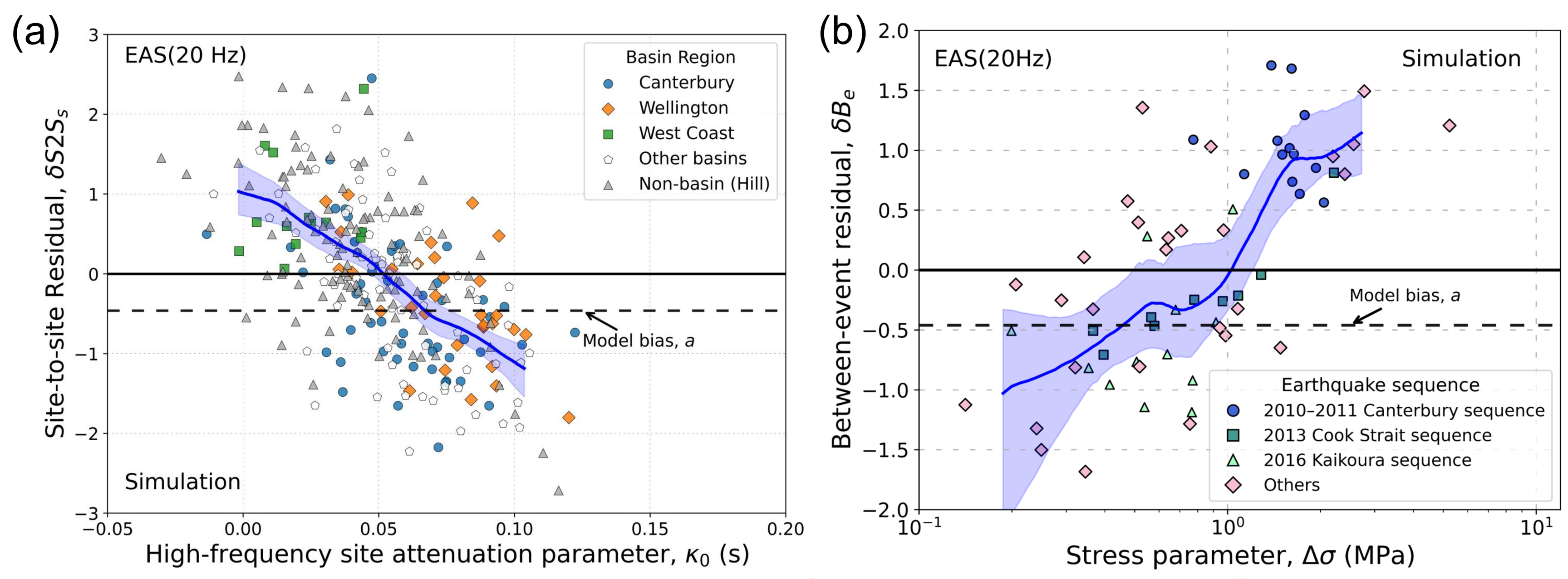


**Figure 4: Relationship between (a) $\delta S2S_s$ and $\kappa_0$, and (b) $\delta B_e$ and $\Delta\sigma$, for EAS(20Hz).**