Ground Motion Simulation Validation with Explicit Uncertainty Incorporation for Small Magnitude Earthquakes in the Canterbury Region

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1. Introduction

Ground motion models are used to predict intensity measures (IM) from seismic events, and are part of the probabilistic seismic hazard framework used for earthquake engineering design. Over recent years there has been a trend towards developing site-specific physics-based ground motion simulation models, however, these models do not yet explicitly incorporate uncertainty, and are intrinsically deterministic.

This study explicitly includes source, path and site uncertainties into physics-based ground motion simulations, in order to account for: inherent modelling restrictions, ground motion randomness and modelling errors. These uncertainties are propagated through the model to produce a range of realisations for a given intensity measure, site and event. Once validated, these probabilistic distributions will provide a more reliable prediction of possible ground motions. Figure 1 illustrates an example of a deterministic and probabilistic response spectra.

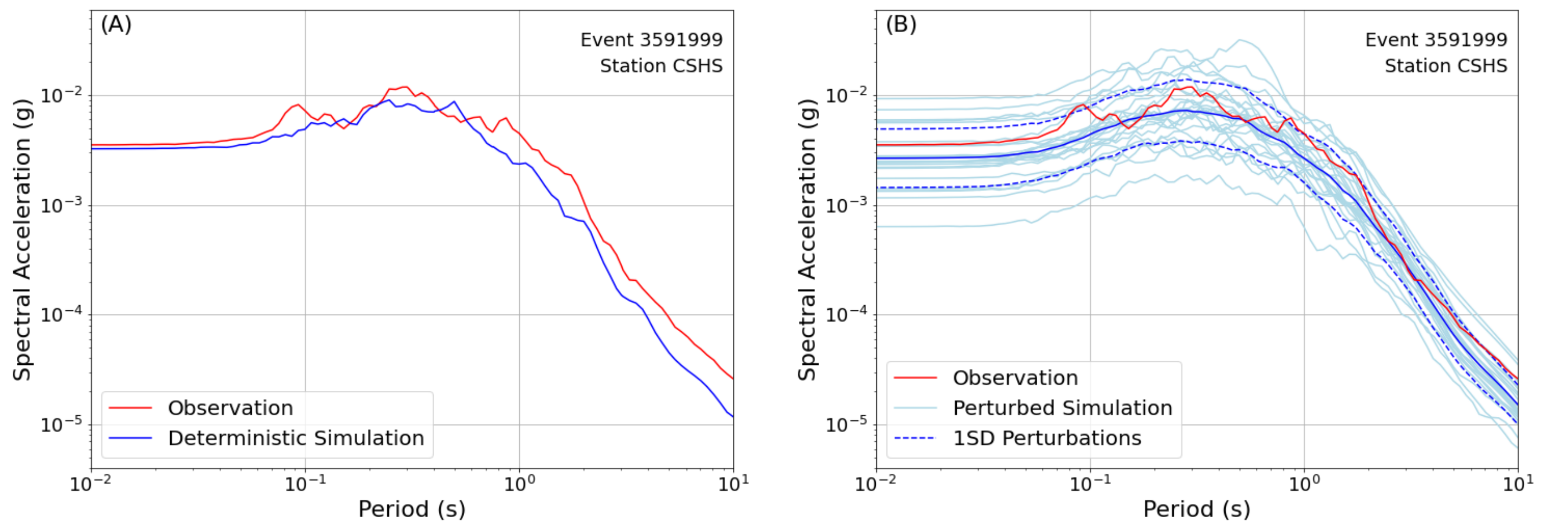

Figure 1: The response spectra for event 3591999 (M_w 4.9, Godley Head) and station CSHS observation and simulation. (A) Ground motion simulation are inherently deterministic. (B) But with explicit uncertainty incorporation they produce intensity measure realisations, with an IM distribution and sigma.

2. Earthquake Events and Simulation Method

This study provides an initial examination of parameter and model uncertainty in a New Zealand ground motion simulation model, by simulating multiple event realisations with perturbed source, path and site parameters.

148 small magnitude (M_w 3.5 – 5) events in Canterbury, as shown in Figure 2, have been selected for this study due to the applicability of a point source model, the wealth of recorded data, and the lack of appreciable off-fault non-linear effects. These factors control the number of uncertainties that should be considered, which provides greater opportunity to identify systematic source, path and site effects, required to robustly investigate the causes of uncertainty.

The simulations utilise the hybrid broadband ground motion simulation approach developed by Graves and Pitarka (2010, 2015, 2016) with modifications from Lee et al. (2020). Crustal seismic velocities are prescribed from the Canterbury Velocity Model (Lee et al. 2017; Thomson et al. 2019), with a resolution of 0.4km. The data and rigour in validation of the Canterbury Velocity Model also assists in reducing the number of uncertainties for the focus of this study.

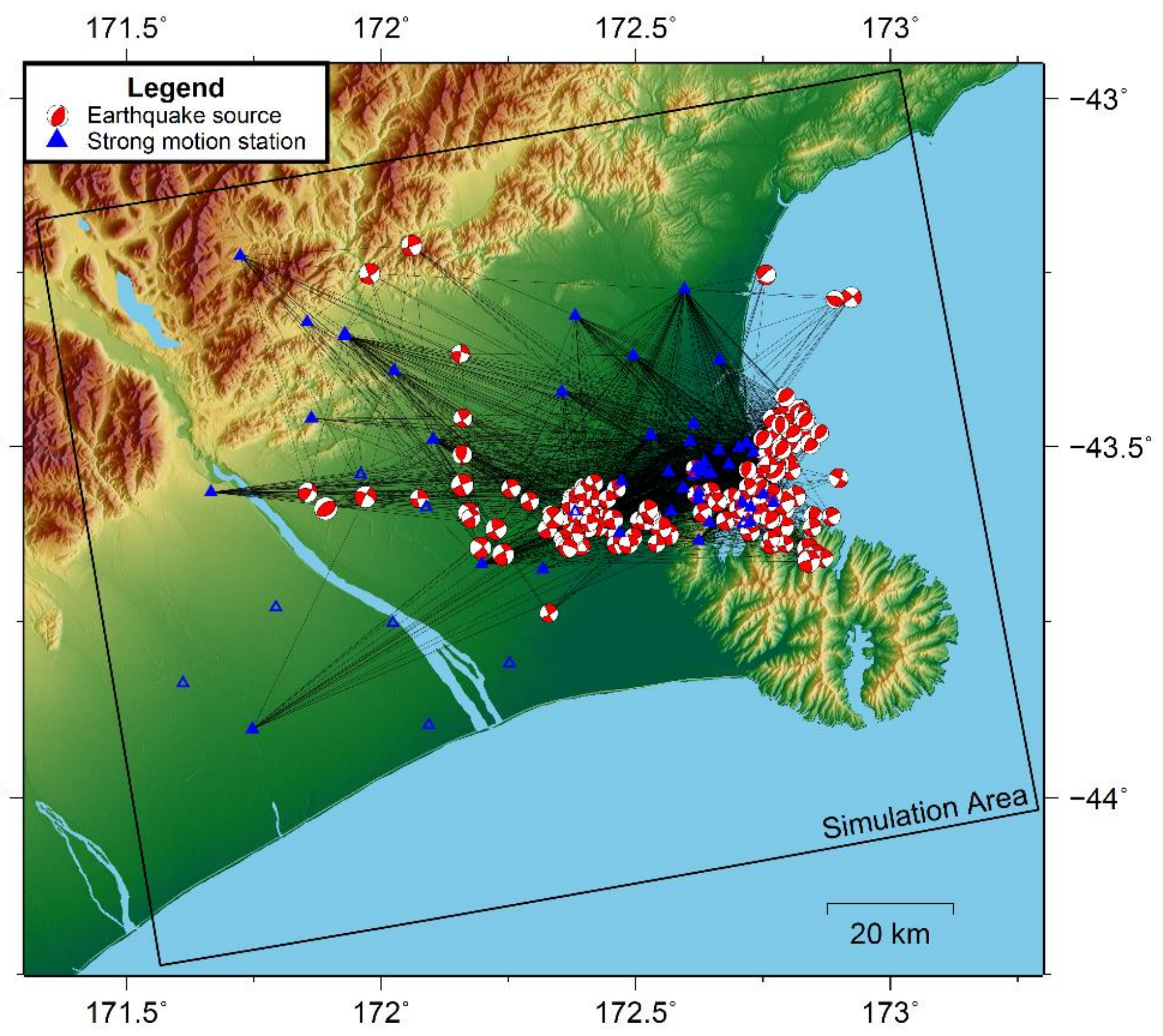

Figure 2: Map of the Canterbury region with the 148 event and 42 station locations considered in this study.

3. Uncertainties Considered

Figure 3 demonstrates a number of distributions and perturbations of uncertainty parameters corresponding to 25 Monte-Carlo realisations for each event and site considered in this initial study. V_{s30} uncertainty is site specific and is therefore not shown.

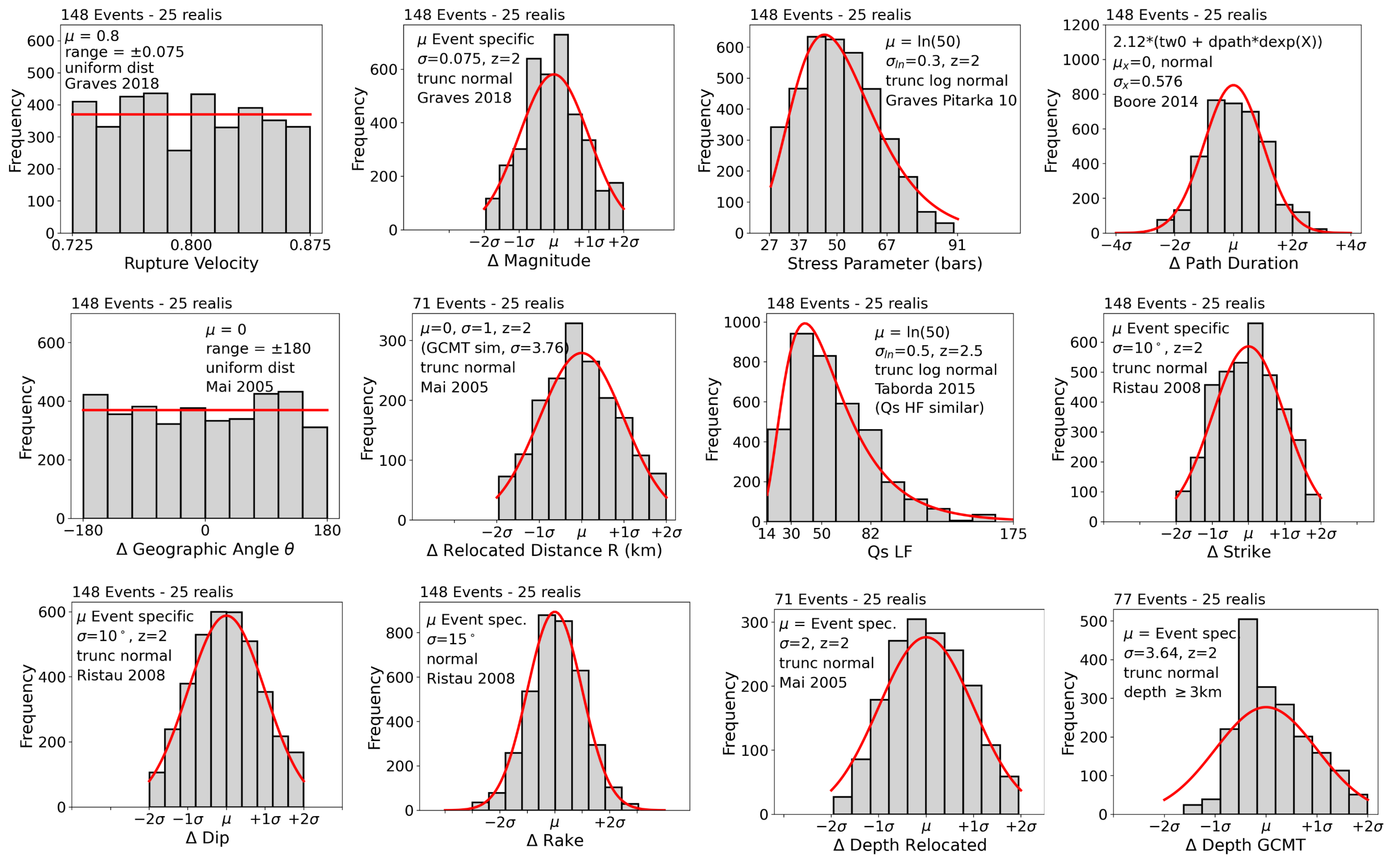

Figure 3: Uncertainty distributions used for parameter perturbations, representing 3700 simulations. The selected uncertainties are associated with: rupture velocity ratio, magnitude, the Brune stress parameter, path duration, geographic location, attenuation, strike, dip, rake, depth and site Vs30.

4. Uncertainty Results for a Single Event

From the simulated ground motions, IMs were generated and compared with observational data, as shown in Figure 4. The simulation realisations generate a range of ground motions for each record.

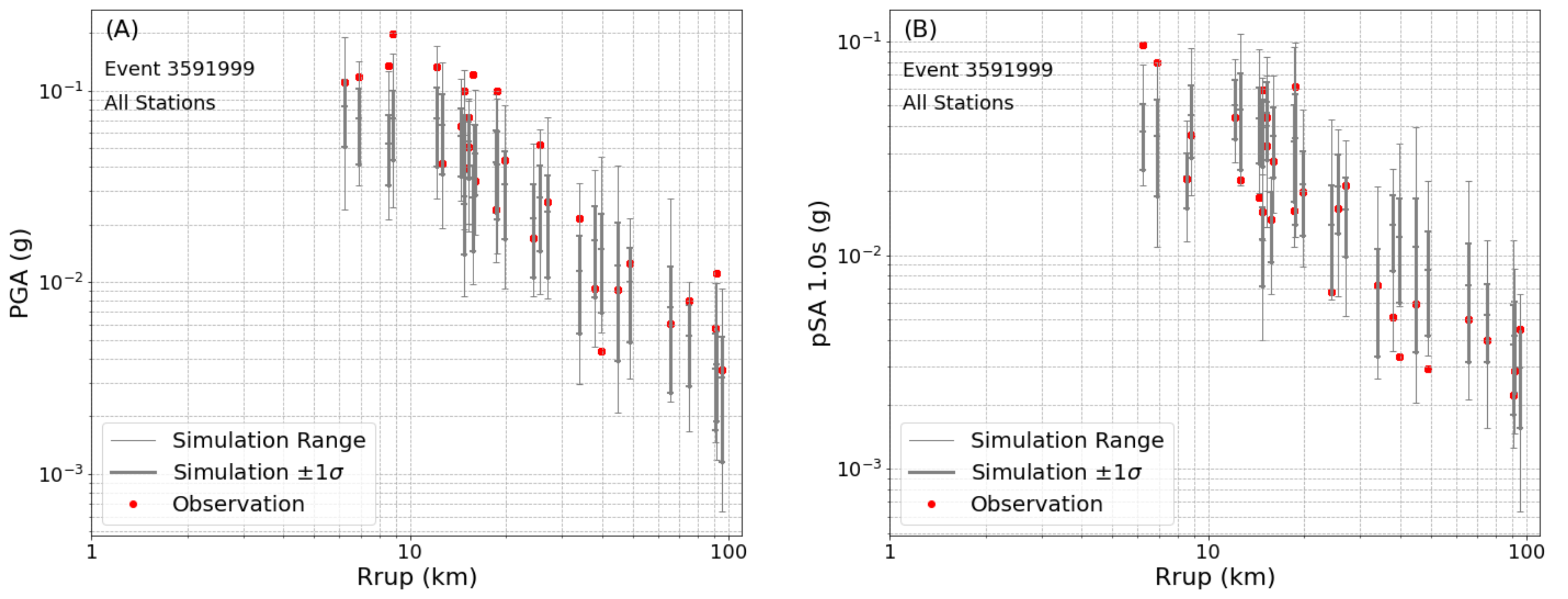

Figure 4: (A) PGA and (B) pSA 1.0s intensity measures with distance, for observations and simulated results from event 3591999 and all recorded stations. For the model bias and uncertainty to be sufficient, the observation should coincide within the simulation range. This does occur at most stations for both PGA and pSA 1.0s.

5. Uncertainty Results for All Events

In order to assess the ground motion simulation results for all events and all sites at once, the normalised residual (Z_p) of all records can be used. Z_p is as calculated using Equation 1.

$$Z_p = \frac{\ln IM_{obs} - \mu_{\ln IM_{sim}}}{\sigma_{\ln IM_{sim}}} \qquad (1)$$

IM_{obs} is the ground motion observation for a single IM

IM_{sim} are the simulated ground motions for a single IM

Z_p can be interpreted such that the simulations are unbiased if the average Z_p is equal to zero. Furthermore, the target standard deviation for Z_p is 1.

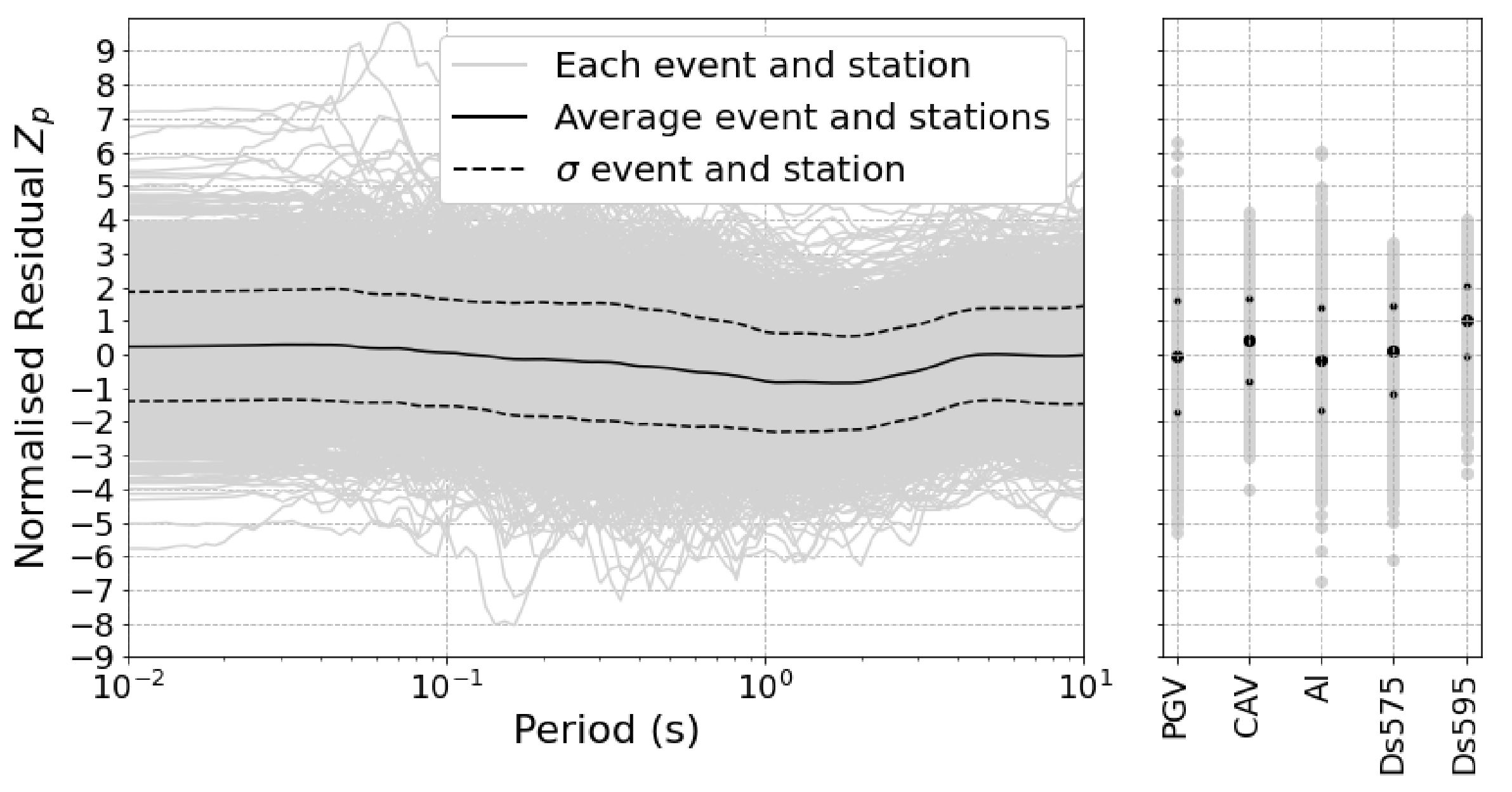

Figure 5 demonstrates that σ_{Zp} is approximately equal to 2 for most intensity measures, indicating the input uncertainties are either too low or more model and/or parameter uncertainties are required.

Figure 5: The normalised residual for all records across a number of intensity measures. These results show that for most events and sites at all intensity measures, more uncertainty is required, as $|\sigma_{Zp}| > 1$.

6. Assessment of Systematic Effects

In order to ascertain where more uncertainty is required, systematic effects of the ground motion residuals are assessed. These are calculated using residuals between observations and simulations for each intensity measure, across all stations and all events (Equation 2). Mixed effects regression is then undertaken to partition the residuals, as per Equation 3. Where a is the model bias, δ_e is the between-event effects component, δ_s is the systematic site-to-site effects component, and δ_{es} is the remaining within-event component. Figure 6 shows the three component results for all pSA intensity measures and all ground motion records.

$$\Delta_{kij} = ln\, IM_{obs\, ij} - \, ln\, IM_{sim\, kij} \qquad (2)$$

$$\Delta_k = a + \delta_e + \delta_s + \delta_\varepsilon \qquad (3)$$

Δ_{kij} is the residual for a given realisation, event and intensity measure.

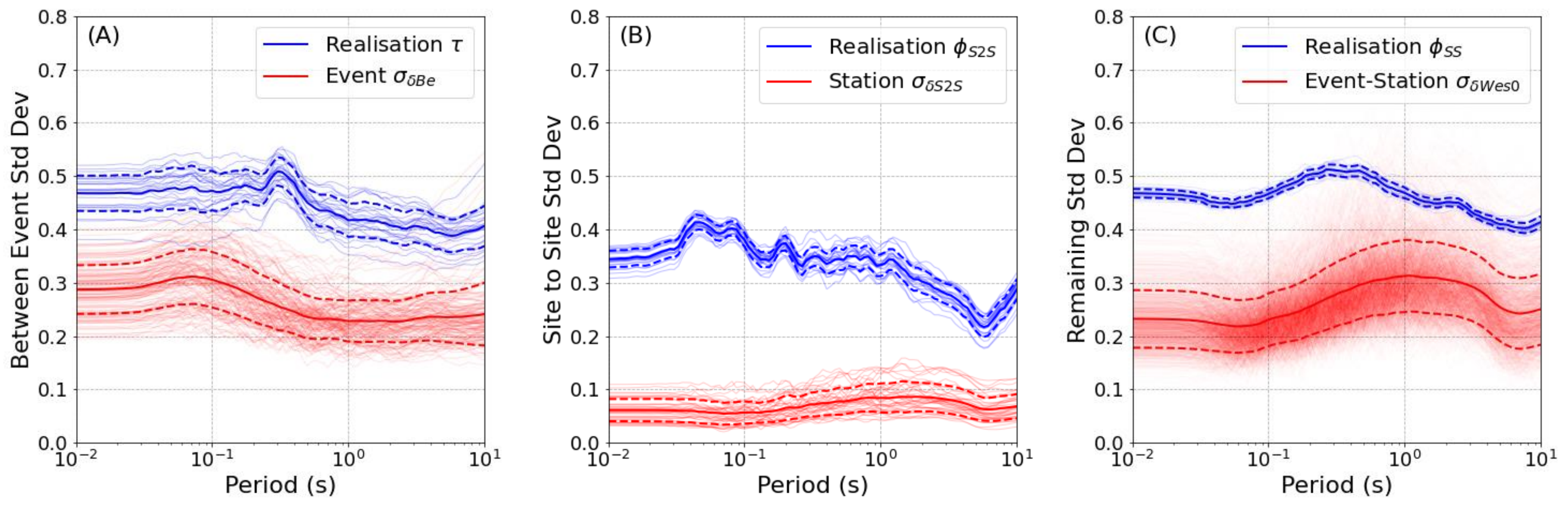

Figure 6: Ground motion residual effects for (A) between events, (B) site-site and (C) the remaining within-event. The realisation results (in blue) represent the variation between different events, sites or paths. The σ results (in red) shows the variation between realisations i.e. the input uncertainty. As these results do not show consistent overlap for all cases, the uncertainty is too low to capture the variation, especially for site uncertainty and short periods.

7. Conclusion

The validation results show that some records have suitable input uncertainty for capturing the observational data (e.g. event 3591999 across most sites). However, the level of uncertainty is insufficient when assessed across all small magnitude Canterbury records at a number of intensity measures. Therefore, further uncertainty input is required to account for additional parameter / modelling assumptions, simplifications or errors in the simulated ground motions.

In future iterations, it is planned to include inputs that account for the uncertainty in: the selected site amplification model, the velocity model's shear wave velocities, and kappa-0. It is also planned to make further refinements to the current model's anelastic attenuation uncertainty. Further variance analysis will also be undertaken to ascertain the performance of the uncertainties that are included, in order to make adjustments where required.