Towards engineering-ready physics-based seismic hazard: the next iteration of Cybershake NZ

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1. What are the next steps in physics-based seismic hazard?

Cybershake New Zealand has shown that physics-based ground motion is viable at national scale. But this demonstration was built on the now-superseded National Hazard Model 2010, with a limited transition frequency, simplified sources, and a flat free surface.

Rebuilding on the National Seismic Hazard Model 2022 (NSHM 2022) multiplies both rupture count and complexity, forcing sharper choices about what we simulate and how we simulate it. Three questions stand between us and engineering-ready hazard:

1. On a finite compute budget, **which ruptures do we simulate?** (Section 2)
2. **How do we generate curved and multi-segment kinematic ruptures?** (Section 3)
3. **How do we reach higher frequencies and richer physics?** (Section 4)

2. Multi-objective rupture sampling

There are 7,162 crustal and subduction ruptures with a non-zero annual rate in the NSHM 2022 (Gerstenberger et al., 2024). Simulating all of them several times is infeasible. So we have to be smarter about selecting which ruptures to simulate and which to leave to surrogate models (Schill & Bradley, 2026). Let Λ be the hazard: the annual rate at which an intensity measure exceeds a given level at a site. Estimating Λ by Monte Carlo over N_i realisations of rupture i gives an estimator $\hat{\Lambda}$ with error

$$\mathrm{E}\left[\left(\hat{\Lambda}-\Lambda\right)^2\right] = \sum_{N_i>0} \lambda_i^2 \frac{P_i(1-P_i)}{N_i} + \left(\sum_{N_i=0} \lambda_i P_i\right)^2, \qquad (1)$$

for λ_i the annual rate and P_i the conditional exceedance probability. Neyman allocation $N_i \propto \lambda_i \sigma_i$, $\sigma_i = \sqrt{P_i(1-P_i)}$, minimises the variance. The bias is reduced by simulating as many large-$\lambda_i P_i$ ruptures as possible. P_i is unknown before simulating, so we estimate it from the NSHM 2022 ground motion logic tree as a surrogate for the simulations. Prior Cybershake NZ allocates by magnitude alone (Equation 2), which is blind to exposure: an M_w 8 beneath Wellington is sampled as often as one in Fiordland.

$$N_i(M_w) := \begin{cases} 14 & \text{if } M_w < 6.0 \\ 27M_w - 148 & \text{if } 6.0 \le M_w \le 8.0 \\ 68 & \text{if } M_w > 8.0 \end{cases} \qquad (2)$$

Simulations also serve users other than PSHA. Surrogate model training prefers uniform coverage of (M_w, R_{rup}), while scenario re-use prefers a prescribed event set. Trade-offs between these objectives are modelling choices. We propose a **sampling logic tree**: independent allocation models, each optimal for one objective, combined under modeller weights.

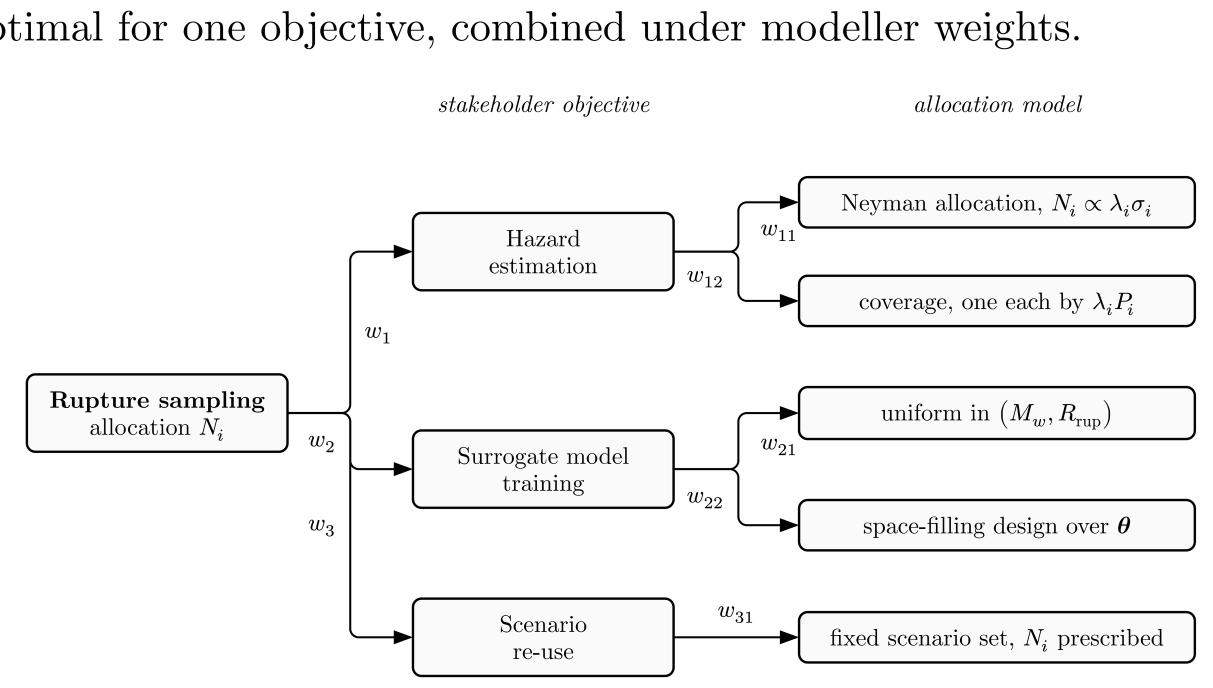

Figure 1: Hypothetical sampling logic tree: the first level splits on the stakeholder objective, the second on the model realising it. Weights on both levels are modelling choices.

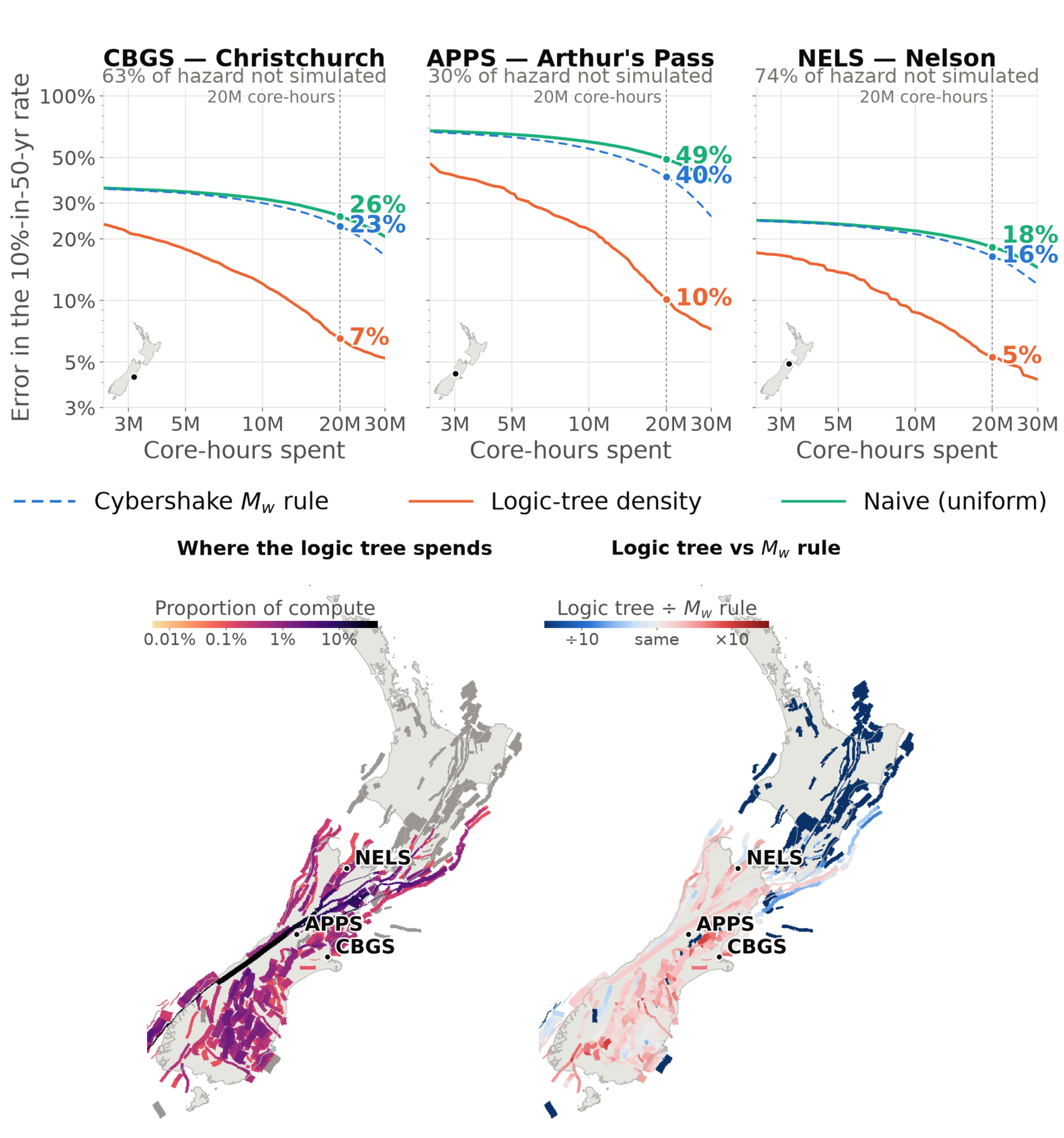

Figure 2: Error reduction bought per core-hour by each allocation model, using a logic tree optimised for South Island crustal hazard. Each panel reports the error of the sampling logic tree at 20 million core-hours, split into bias and noise.

3. Multi-segment rupture generation

Kinematic rupture generators following Graves–Pitarka (Pitarka et al., 2022) assume a connected sequence of planar segments, but the NSHM 2022 crustal dataset consists of multi-segment and curved ruptures. We need an automated approach to generating such ruptures at scale.

We propose a heuristic rupture propagation algorithm that bootstraps multi-segment ruptures from **any** kinematic rupture generator. Candidate joins are ranked by endpoint separation and accepted joins form a tree rooted at the hypocentre, fixing the traversal order and every segment's entry point. Segments are generated independently, seeded with the arrival time at their entry point. Onset time stays causal and consistent without modifying the generator.

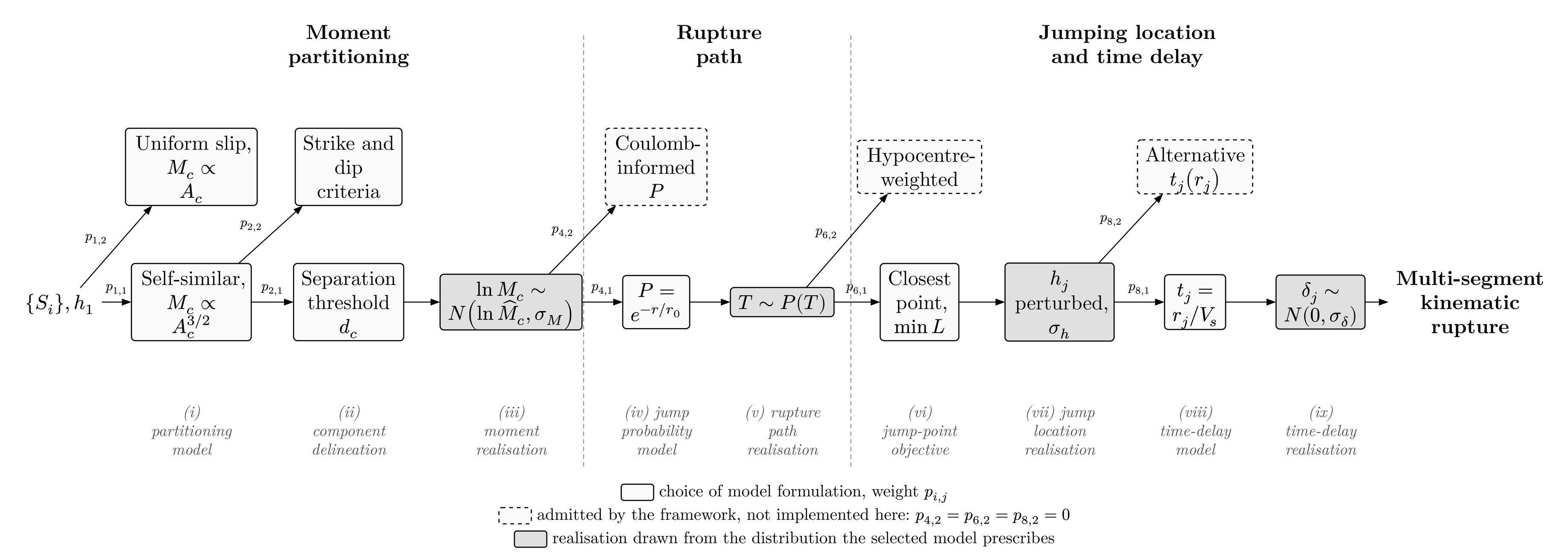

Figure 3: Logic tree for the generation of a multi-segment kinematic rupture, over the three components of the framework. One left-to-right traversal is one realisation of the generator.

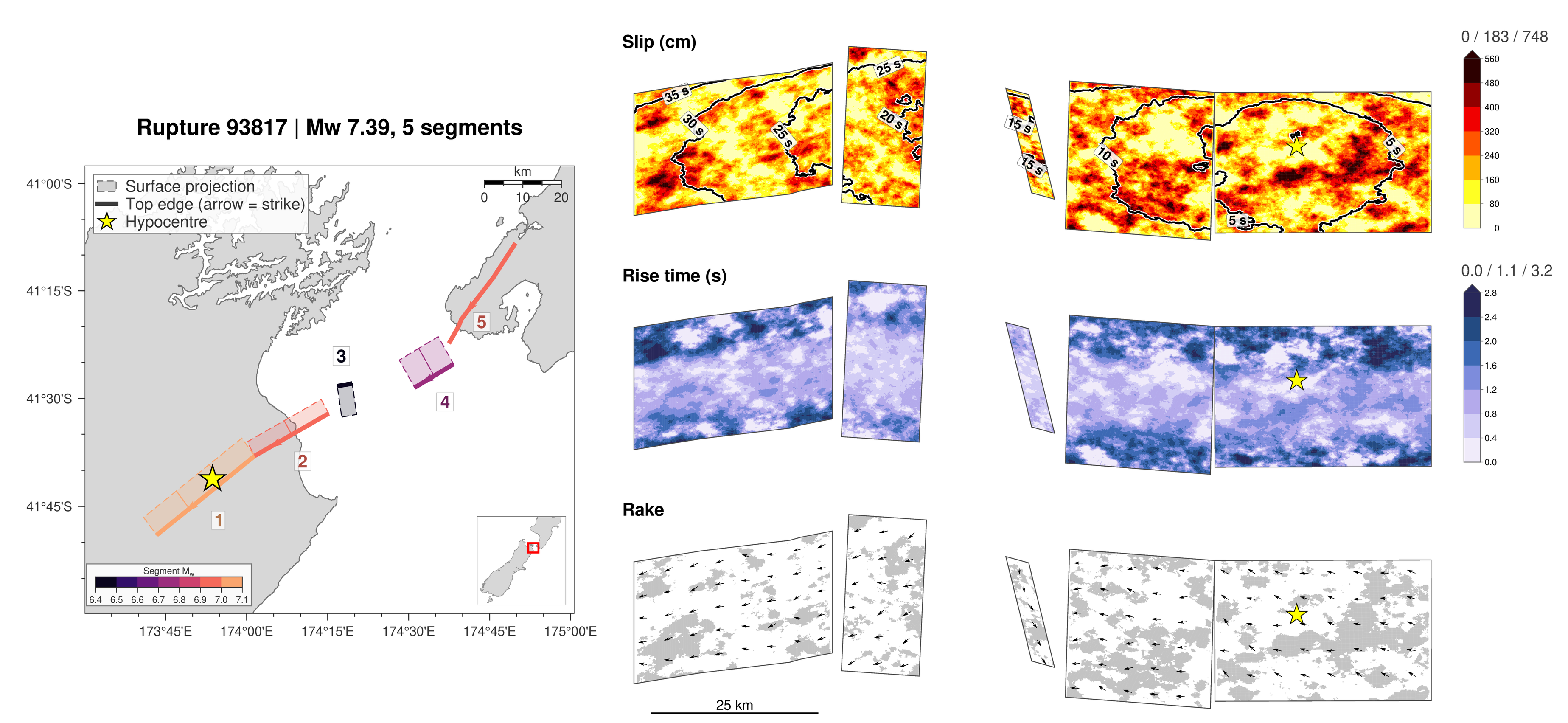

Figure 4: A generated Cook Strait multi-segment rupture from the NSHM 2022. Left: plan view of the participating segments. Right: slip, rise time, and rake for the generated rupture; onset-time contours (labelled in seconds) run continuously across the segment joins.

4. Adopting the SW4 wave propagation code

Basin and topographic effects are decisive for engineering applications, but previous Cybershake NZ iterations could not represent them: the free surface was flat and the grid uniform, so topography was squashed or bulldozed into the velocity model and the near surface was under-resolved at the frequencies where basin effects matter. Seismic Waves, 4th order (SW4) (Petersson & Sjögreen, 2015) removes both compromises. In SW4, topography is native on a curvilinear mesh, and depth-dependent refinement makes the grid finer in the near surface, where the lowest V_S binds $f_{\max}$, and coarser at depth, so the $O(h^{-4})$ cost is paid only in the shallow blocks.

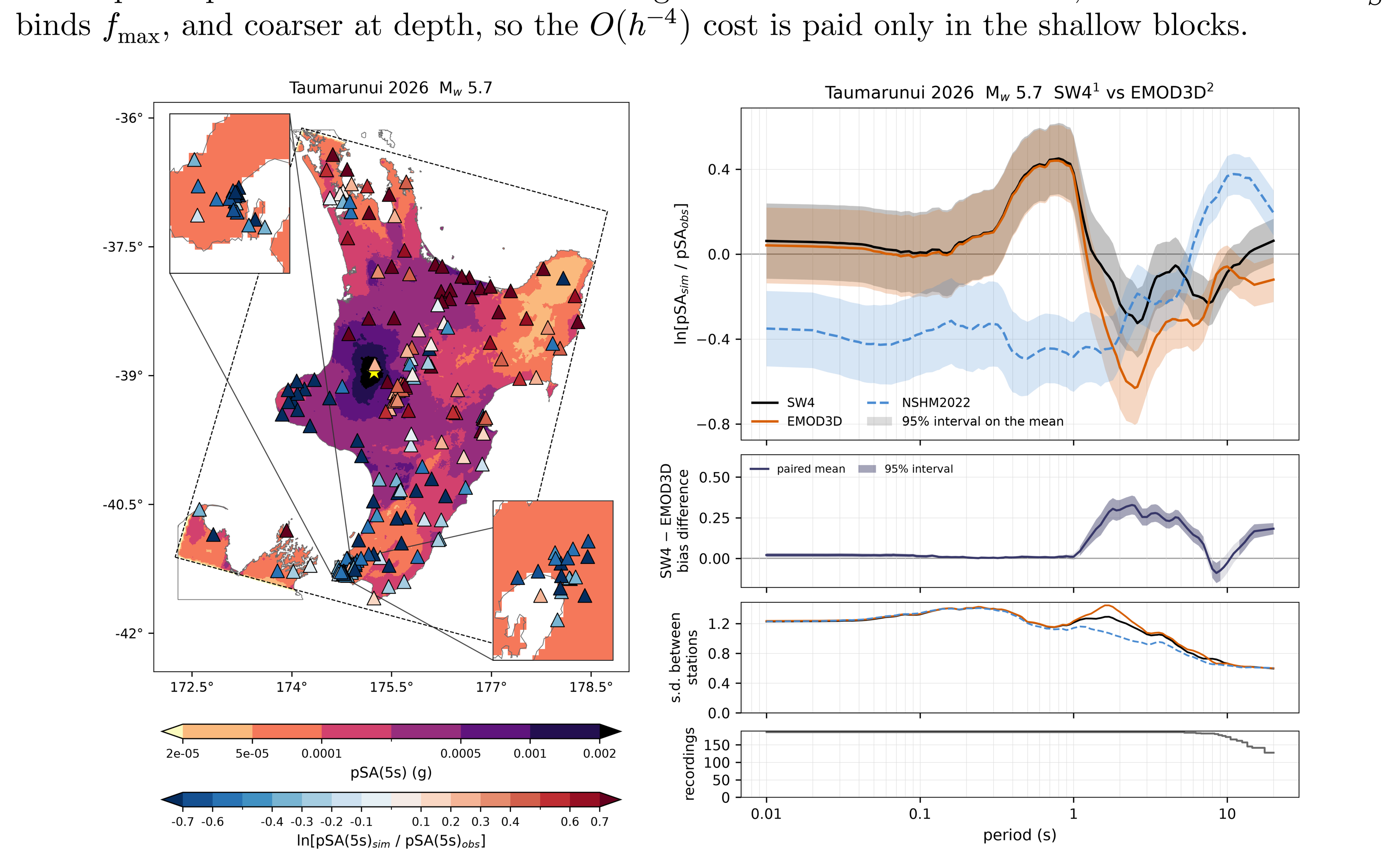

Figure 5: SW4 calculated intensity measures (left) and pSA bias comparison (right) for the recent M_w 5.7 rupture in Taumarunui.

Taumarunui is a single event. This iteration of Cybershake NZ will be accompanied by a validation counterpart: the same SW4 workflow applied to the full New Zealand ground motion database, assessed under a mixed-effects residual analysis framework.

References

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