The 2022 Aotearoa New Zealand National Seismic Hazard Model: Process, Overview, and Results

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ABSTRACT

The 2022 revision of Aotearoa New Zealand National Seismic Hazard Model (NZ NSHM 2022) has involved significant revision of all datasets and model components. In this article, we present a subset of many results from the model as well as an overview of the governance, scientific, and review processes followed by the NZ NSHM team. The calculated hazard from the NZ NSHM 2022 has increased for most of New Zealand when compared with the previous models. The NZ NSHM 2022 models and results are available online.

KEY POINTS

- We develop a fundamental revision of the Aotearoa New Zealand National Seismic Hazard Model (NZ NSHM 2022).
- The results are an increase in forecast hazard across most of New Zealand.
- The increased hazard results from changes to both the rupture and ground-motion modeling components.

INTRODUCTION

The 2022 revision of New Zealand National Seismic Hazard Model—Te Tauira Matapae Pūmate Rū i Aotearoa (NZ NSHM 2022) represents a fundamental revision of the NZ NSHM across all components. It is the first revision since 2010 (Stirling *et al.*, 2012) and the first with fundamental changes since 2002 (Stirling *et al.*, 2002). The aims of the 2022 revision were to update the model using advances in scientific understanding and modeling methods, and to use the significant amount of data that has been collected over the last two decades.

The NZ NSHM is used extensively for informing decision making in New Zealand by both government and private industries. To this end, scientific working group and review processes were designed with the goal of facilitating the development of the best estimate of the hazard and the range

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TABLE 1
Topics and Bibliographic References for Component Publications of the New Zealand National Seismic Hazard Model (NZ NSHM) 2022 Seismicity Rate Model

Topic	Bibliographic References
Consistent magnitudes over time for the revision of the New Zealand National Seismic Hazard Model	Christophersen *et al.* (2022, 2024)
New Zealand National Seismic Hazard Model 2022: Earthquake recurrence derivation from paleoseismic data and probability of detection: Details of the paleo-timings constraint data	Coffey *et al.* (2022, 2024)
New Zealand fault rupture depth model version 1.0: A provisional estimate of the maximum depth of seismic rupture on New Zealand's active faults	Ellis *et al.* (2022, 2024)
New Zealand National Seismic Hazard Model framework plan. The starting work and priorities plan	Gerstenberger, Houtte, *et al.* (2020)
Accounting for earthquake rates' temporal and spatial uncertainties through the least-information forecasts uniform rate zone models and negative binomial temporal model	Iturrieta, Gerstenberger, Rollins, Van Dissen, *et al.* (2022, 2024a, 2024b)
Geodetic deformation model for the 2022 update of the New Zealand National Seismic Hazard Model	Johnson *et al.* (2022, 2024)
New Zealand paleoseismic site database: Data dictionary	Litchfield (2022)
New Zealand paleoseismic site database: Design and overview of version 1.0	Litchfield *et al.* (2022, 2024)
Spatial distribution of earthquake occurrence for the New Zealand National Seismic Hazard Model revision The hybrid distributed seismicity model	Rastin *et al.* (2022, 2024)
An augmented New Zealand earthquake catalogue, event classifications, and models of the depth distribution of shallow earthquakes in the greater New Zealand region	Rollins *et al.* (2021)
The magnitude–frequency distributions of earthquakes in the greater New Zealand region, and along the Hikurangi–Kermadec and Puysegur subduction zones, and their uncertainties, with application to the 2022 New Zealand National Seismic Hazard Model *N*-value and *N*-scaling derivation	Rollins *et al.* (2022), Rollins, Christophersen, *et al.* (2024), and Rollins, Gerstenberger, *et al.* (2024)
New Zealand Community Fault Model–version 1.0	Seebeck *et al.* (2022, 2023)
Selection and evaluation of magnitude–area scaling relations for update of the New Zealand National Seismic Hazard Model	Stirling *et al.* (2021, 2023)
Testing and Evaluation of the New Zealand National Seismic Hazard Model	Stirling *et al.* (2022, 2023)
A seismogenic slab source model for New Zealand	Thingbaijam, Gerstenberger, *et al.* (2022)
A simple model of faulting patterns for distributed seismicity in New Zealand strike constraints for the distributed seismicity model-based ground-motion calculations	Thingbaijam, Van Dissen, *et al.* (2022) and Rattenbury (2022)
Average coseismic slip profiles slip-profile considerations for the inversion-based fault model	Thingbaijam, Rattenbury, *et al.* (2022)
New Zealand National Seismic Hazard Model 2022: Geologic and subduction interface deformation models	Van Dissen *et al.* (2022, 2024)

within which it falls. The NZ NSHM 2022 was developed in close collaboration with key users to facilitate the users' understanding of the details and assumptions of the model, and to make sure that the model is useful for application, in addition to furthering our understanding of earthquake occurrence. Key uses of the outputs are to inform requirements related to meeting building code requirements and for loss modeling needs in New Zealand. The revision was required to be completed in approximately two years, from start to finish, to meet timelines for updating building code-related requirements.

The NZ NSHM 2022 is itself a collection of many component models that are used to make up the overall probabilistic seismic hazard analysis (PSHA). The details of the component models of the NZ NSHM 2022 are introduced in numerous other articles in the *Seismological Research Letters* and *Bulletin of the Seismological Society of America* special focus section and special issue, respectively, on seismic hazard analysis and in multiple technical reports (Tables 1 and 2). This article provides a brief overview of key components and processes involved in the NZ NSHM 22.

TABLE 2
Topics and Bibliographic References for Component Publications of the New Zealand National Seismic Hazard Model (NZ NSHM) 2022 Ground-Motion Characterization Models

Topic	Bibliographic References
2021 New Zealand ground-motion database	Hutchinson *et al.* (2022, 2024)
New Zealand site-characterization database	Wotherspoon *et al.* (2022)
Evaluation of empirical ground-motion models	Lee *et al.* (2022, 2024)
A model for the distribution of the response spectral ordinates from New Zealand crustal earthquakes based upon adjustments to the Chiou and Youngs (2014) response spectral model	Stafford (2022, 2024)
Backbone ground-motion models for crustal, interface, and slab earthquakes in New Zealand	Atkinson (2022, 2024)
Impact of directivity on probabilistic seismic hazard calculations in New Zealand	Weatherill (2022) and Weatherill and Lilienkamp (2024)
Hazard sensitivities associated with updated ground-motion characterization models	Bora *et al.* (2024)

At a high level, the component models can be broken into two groups: (1) the seismicity rate model (SRM), which comprises multiple models that forecast earthquake rupture locations, rates, and magnitudes; and (2) the ground-motion characterization model (GMCM), which also comprises multiple models and forecasts the ground shaking for each possible rupture. Gerstenberger *et al.* (2022, 2024) provide a detailed overview of the SRM, including commentary on the development of the components described in the SRM-related articles and reports listed in Table 1. Bradley *et al.* (2024, this volume) provides a detailed overview of the GMCM, with further development presented in the GMCM-related articles and reports listed in Table 2.

To facilitate the aim of the NZ NSHM 2022 revision of using the best available science, a participatory peer review process was applied (see the Participatory peer review section). When compared with past NZ NSHMs, there have been significant revisions to all model components and underpinning datasets, which result in significant changes in hazard for much of New Zealand. In this overview, we discuss the process supporting the development of the NZ NSHM 2022 model (including the participatory peer review process), provide a brief overview of the main model components and logic tree, and discuss the final hazard results. In the next section, we outline the key changes between the current and past NZ NSHMs, and in subsequent sections we detail the changes in hazard that have resulted, and identify their causes.

Model changes from past New Zealand NSHMs

Changes from past NZ NSHMs range from procedural to philosophical to scientific or new-data driven. Here we highlight those key changes to the model when compared with the previous NZ NSHMs. These are either discussed in this article or in the article identified with the specific topic.

Key overall changes in the 2022 NSHM 2022 are identified as follows:

- modeling of a large range of epistemic uncertainty in both SRM and GMCM in the final hazard results in 2022 and no epistemic uncertainty in the prior models;
- a 100-year time-dependent hazard forecast time window in 2022 and time-independent forecasts in prior models;
- testing of component model performances throughout model development and a final hazard testing phase of statistical testing of NSHM forecasts against observed ground shaking (Stirling *et al.*, 2022, 2023) and limited testing explicitly in prior model development;
- site parameters in terms of V_{S30} (time-averaged shear-wave velocity in upper 30 m of the geologic column) instead of New Zealand site class (Standards New Zealand, 2004);
- use of structured science working group procedures and participatory peer review panel;
- open availability of the model via online tools;
- open availability of the model components and all datasets used to constrain the model. Model available in OpenQuake format (Pagani *et al.*, 2014); and
- extensive documentation.

Key changes to the SRM (Gerstenberger *et al.*, 2022, 2024) include:

- newly developed New Zealand Community Fault Model (CFM) version 1.0 (Seebeck *et al.*, 2022, 2023);
- development of the maximum fault rupture depth model (Ellis *et al.*, 2022, 2024);
- new paleoseismic database (Litchfield *et al.*, 2022, 2024);
- use of both geologic data and geodetic data to characterise upper-plate fault-slip rates (Johnson *et al.*, 2022, 2024; Van Dissen *et al.*, 2022, 2024) instead of primarily using geologic data;
- homogenized moment magnitude earthquake catalog instead of hetergeneous magnitudes and a heavy reliance on local magnitude (Christophersen *et al.*, 2022, 2024);
- revised magnitude-area scaling relations (Stirling *et al.*, 2021, 2023);
- crustal fault ruptures with a range of magnitude and fault connectivity uncertainties (i.e., not single-magnitude characteristic ruptures; Gerstenberger *et al.*, 2022, 2024);

- considerations of 1000s of crustal ruptures on known faults instead of 500 or fewer ruptures (Gerstenberger *et al.*, 2022, 2024);
- the addition of complex crustal fault ruptures and accounting for low probability high-impact events (Gerstenberger *et al.*, 2022, 2024);
- consideration of a large range of magnitude–frequency distributions (MFDs) for crustal earthquakes instead of a single MFD (Gerstenberger *et al.*, 2022, 2024; Rollins *et al.*, 2022; Rollins, Christophersen, *et al.*, 2024; Rollins, Gerstenberger, *et al.*, 2024);
- joint fitting of multiple earthquake occurrence datasets using the Uniform California Earthquake Rupture Forecast 3 (UCERF3; Field *et al.*, 2013) recipe (Gerstenberger *et al.*, 2022, 2024);
- extension of the Hikurangi interface to include the Hikurangi–Kermadec interface north to the Louisville Ridge (Gerstenberger *et al.*, 2022; 2024; Van Dissen *et al.*, 2024);
- consideration of a larger range of magnitudes and multiple MFDs on the Hikurangi–Kermadec and Puysegur interfaces (Gerstenberger *et al.*, 2022; 2024; Rollins *et al.*, 2022; Rollins, Christophersen, *et al.*, 2024; Rollins, Gerstenberger, *et al.*, 2024);
- consideration of 1000s of potential ruptures on both the interfaces instead of 10 or fewer (Gerstenberger *et al.*, 2022, 2024);
- improved occurrence models and accounting for uncertainty for low-seismicity regions (Iturrieta *et al.*, 2022, 2024a);
- hybrid model of multiple components using earthquake catalog, geologic, and geodetic datasets to form distributed seismicity models instead of a single catalog-based smoothed seismicity model (Gerstenberger *et al.*, 2022, 2024; Rastin *et al.*, 2022, 2024);
- use of finite ruptures for distributed seismicity model, including significantly revised fault orientation, and mechanism constraints instead of point sources (Thingbaijam, Rattenbury, *et al.*, 2022);
- updated earthquake depth distributions for use in the distributed seismicity models, incorporating relocations of NZ seismicity since 2000 (Rollins *et al.*, 2021);
- development of a paleoearthquake recurrence interval dataset and time dependence applied to all crustal faults in the model (Coffey *et al.*, 2022, 2024; Gerstenberger *et al.*, 2022, 2024);
- rates of earthquakes not fully declustered in space and not declustered in total rate compared with a fully declustered model in 2010 (Gerstenberger *et al.*, 2022, 2024; Rastin *et al.*, 2022, 2024);
- modeling of the non-Poisson uncertainty in mean forecast rate instead of a strictly Poisson forecast (Gerstenberger *et al.*, 2022, 2024; Iturrieta *et al.*, 2022, 2024a; Rollins *et al.*, 2022; Rollins, Christophersen, *et al.*, 2024; Rollins, Gerstenberger, *et al.*, 2024); and significantly revised intraslab occurrence model including use of finite ruptures (Thingbaijam, Gerstenberger, *et al.*, 2022; Thingbaijam *et al.*, 2024).

For the GMCM, key changes include:

- a new ground-motion database (Hutchinson *et al.*, 2022);
- a new site-characterization database (Wotherspoon *et al.*, 2022);
- use of multiple modern international ground-motion models (GMMs) with constraints derived from the recent earthquakes around the world such as Next Generation of Attenuation (NGA)-West2 and Next Generation of Attenuation-Subduction (NGA-Sub) instead of a single GMM as in the past models (Mazzoni *et al.*, 2022). It involves seven GMMs for crustal earthquakes, including four international models. Four GMMs for each, subduction interface and intraslab earthquakes, including three international models (Abrahamson and Guelerce, 2020; Kuehn *et al.*, 2020; Parker *et al.*, 2022);
- two NZ-specific backbone models developed using the NZ ground-motion database (Atkinson, 2022; Stafford, 2022) that inherently prescribe epistemic uncertainty (through upper and lower branches) in their modeling framework;
- a GMCM and logic tree, which provide constraint on the median as well as aleatory uncertainty over a larger range of magnitudes and distances than in the past models (Bradley *et al.*, 2022, 2024);
- use of heteroscedastic aleatory uncertainty (σ) models in the GMCM that allows for reduction in σ due to soil nonlinearity (Bradley *et al.*, 2022, 2024); and
- revised backarc distance-scaling corrections (Abrahamson *et al.*, 2016) accounting for higher attenuation in the southwestern region of the North Island (Bradley *et al.*, 2022, 2024).

NSHM TECHNICAL OVERSIGHT, PARTICIPATORY PEER REVIEW, AND SCIENCE DECISION-MAKING STRUCTURE: OPTIMIZING THE USE OF EXPERT JUDGMENT

There were three main components to NZ NSHM 2022 oversight: (1) project governance; (2) science decision making; and (3) peer review (Christophersen and Gerstenberger, 2024). Project governance is not discussed here. However, because the technical decision making and review processes were critical contributors to the NZ NSHM 2022 with each significantly affecting the results of the model, we will discuss them. We suggest that such processes are critical to any large science project and are often not given sufficient attention. The use of expert judgment is intrinsic to the technical decision making in the NZ NSHM 2022, as it is with any NSHM; it can be divided into two types with the second being dependent on the first. Over the course of the project, a working group process and a technical advisory group (TAG) were used to define the project, and to make the scientific decisions necessary to produce the final model. This detailed process allowed for multiple scientists to contribute to, debate the merits of, and to develop a thorough understanding of each component of the model, and also how the components and modeling choices interacted with one another. Building from this, and using a subset of the scientists who were involved in the working group and TAG process, a structured expert elicitation process was used to produce the weights on logic tree branches. The scientists contributing to the weighting were chosen from NSHM and TAG participants; it was not possible for external scientists to have the depth of subject-relevant knowledge and an understanding of the complexities of the interactions within the NSHM, as did those who participated in two years of model debate and exploration. Potential bias is minimized through choosing a diverse range of experts and through a structured elicitation process, as described in Christophersen and Gerstenberger (2024). These processes are detailed in the following sections.

Science working groups

The science development was done via four working groups, two of which had a substantial number of subworking groups. The main working groups were: SRM—development of the forecast models of earthquake ruptures; GMCM—development of the ground-shaking forecast models; service delivery—development of the computational infrastructure in support of the science and model process; and Core Team—overall strategic coordination across all working groups and for key modeling decisions.

The working group process was overseen by "The Core Team," which was tasked with handling strategic science and planning decisions that could not be made at the level of other working groups. This team met either weekly or biweekly for the duration of the project. Each working group had a weekly or biweekly top-level meeting. A broad call was made for participation, and attendance was open to any scientist who requested to attend. Within each working group, there were multiple subworking groups. Each of these working groups had regular weekly or biweekly meetings. The aim was to create a relatively flat structure where the ultimate responsibility for delivery of the final NSHM sat with the project lead, but strategic and science decisions were made via the working group structures; ~50–60 scientists and engineers from many institutions and nations were involved in the project at some level.

Participatory peer review

The NZ NSHM 2022 was initially set up allowing just two years from project initiation to a final reviewed and publicly available model. This short-time schedule required that we use a participatory peer review process where the reviewers were actively engaged throughout the life of the project. A 17 member TAG formed the participatory peer review panel, and was composed of two subgroups: science experts and technical end-users. The TAG members were chosen based on the following criteria: (1) science-expert TAG members were selected to cover a broad range of experience, topical knowledge (both of PSHA, but also its constituent disciplines more broadly), diversity, and personality types (e.g., ranging from challengers to observers) based on guidelines in Christophersen and Gerstenberger (2021); and (2) technical end-user TAG members were selected to cover geotechnical and structural engineering, and insurance and reinsurance. Engineering TAG members were either nominated by a relevant NZ engineering technical society, or their selection was discussed with the technical society.

The size of the TAG was chosen to balance the need for efficient and productive meetings, and the need for broad engagement. About 17 members were about evenly split between science experts and technical end-users. The primary focus of the TAG was to provide ongoing review and advice to the NZ NSHM 2022 team as the model was developed. This occurred through four main avenues:

1. formal TAG meetings where the entire TAG was present, meeting roughly every two months;
2. participation in biweekly TAG-aimed science working group meetings, with separate meetings and participants for the SRM, GMCM, and service delivery teams;
3. discussions either through attendance at regular working group meetings or other ad hoc meetings as necessary; and
4. topic-targeted discussions when technical reports were first submitted to the TAG for review (this was not necessary for all reports).

A benefit of this process was that the project team was able to adapt to advice from the TAG and provide feedback to requests in real time. The aim was to reduce the number of modeling decisions that were unknown to the TAG at the time reports were delivered to them and, therefore, to allow for the most informed review that was possible on such a large project in such a short timeframe. This meeting-heavy operational procedure provided the most informative and influential contribution of the TAG advice. The second goal was to review and provide advice based on the 30 technical reports that document the NZ NSHM 2022 (see Tables 1 and 2). The reports were available for all TAG members to provide comment on; however, for most reports, two TAG members were specifically requested to provide comment and review. When insufficient expertise was available in the TAG, external reviewers were sought to provide formal comment. The TAGs role was advisory, and the NSHM team aimed to incorporate the recommendations of the TAG and generally were able to do so. If the project team disagreed with the recommendations, or the recommendations were not practical to implement within the time constraints of the project, there was a formal documented response to the TAG. The exact review process varied depending on the topic but broadly followed:

1. The draft report was provided to all TAG members. All TAG members were invited and encouraged to review the report. When applicable, draft reports were accompanied by an ~1–2 hr meeting involving the report lead author(s), relevant NSHM members, and TAG members focussed on the details of the report;
2. TAG members provided written review of the draft report;
3. the report authors, together with the wider NSHM team, as was necessary, addressed the review comments;
4. if all recommendations were applied, the draft was revised, finalized, and made available to the TAG;
5. if some recommendations were not applied, a formal response to these recommendations was made. If these were minor details, the report was finalized (and discussed with TAG as was practicable). If there were significant details to the response, the specifics were discussed with the TAG prior to finalization of the report;
6. upon finalization, all NZ NSHM 2022 reports were issued a DOI and made publicly available through the NZ NSHM 2022 website (see Data and Resources).

The third goal of the TAG process was to increase engagement of the NZ NSHM 2022 team with key members of the end-user community. The goals of this were threefold: (1) to facilitate mutual understanding between the NSHM and end-users of key decisions in building the NZ NSHM 2022; (2) to allow for end-user input into key decisions of the model and its outputs; and (3) a longer term goal of increasing the awareness and understanding of the NSHM in the NZ engineering community. Finally, an additional "Assurance Review" was performed by an international panel charged with reviewing both the TAG and working group processes. The results of this review were positive and supportive of the procedures used (Cowan *et al.*, 2022).

In both the prereport development phase and in the report reviewing phase, the participatory peer review process had a significant impact on the technical details of the NZ NSHM 2022. Unquestionably, the greatest impact was in the development of the concepts and details throughout the model development and prior to the writing of the final reports; this was consistent with the goal of minimizing the need for late stage and rushed changes in the model. The impacts came both in the form of helping to guide decisions and in critical analysis of model choices, details, and outputs. The design and setup of the participatory peer review process was a critical part of the NZ NSHM 2022 leading to a better understood and defensible forecast. For this reason, we feel peer review processes are an important contributor to the development of such models, and require care and scrutiny in their own development. Typically journal-based peer review is perceived as a gold standard for review of such a national-scale seismic hazard models. However, typical journal review processes were not possible to use within the time constraints of this project. In addition, journal review peer processes are unlikely to be able to provide a comprehensive and well-informed review of such a large and complex project that contains many dependent components and that are detailed in more than 30 technical reports. For this reason we argue that journal peer review processes can be an important contributor, when possible, for the development of NSHMs; however, in most cases, such reviews are unable to provide as thorough and informative of a review as is provided using the processes we have outlined.

Structured expert elicitation

We also applied the philosophy that, due to the level of uncertainty in seismic hazard science, it is unreasonable, and not helpful, to obtain consensus in the degree-of-belief weights for the key epistemic uncertainties. Therefore, for eliciting the weights for the logic-tree branches we also followed a procedure that allows for including the range of scientific judgment from across the NSHM team, including the TAG. For a full description of the structured expert elicitation procedure please see Christophersen and Gerstenberger (2024). We have followed a procedure as outlined in Christophersen and Gerstenberger (2021) and is one similar to that applied in many other industries. Some examples are, for example, nuclear waste repository (Scourse *et al.*, 2015), sea level rise (Bamber and Aspinall, 2013), volcano risk (Wadge and Aspinall, 2014), carbon capture, and storage (Gerstenberger *et al.*, 2015); however, there have been only a few applications in seismic hazard (e.g., Gerstenberger *et al.*, 2014, 2016; Griffin *et al.*, 2018, 2020; Meletti *et al.*, 2021). Three of the main components are: (1) the method used to derive the expert judgment; (2) the selection of the "experts"; and (3) the elicitation workshop design. The goal is to reduce the use of subjectivity in the method and to obtain unbiased and optimal weights for the logic-tree branches being assessed. This procedure employs a structured expert elicitation method (Cooke, 1991; Cooke and Goosens, 2000) that is designed to produce optimal weighted average results across a group of experts by calibrating the experts. At the core of the method is a set of calibration questions that aim to assess how well the experts assess the uncertainty in their own knowledge; this is done to help control for overconfidence and underconfidence. This happens through two aspects: (1) deriving weights for each of the experts based on their relative overconfidence or underconfidence; and (2) providing feedback to the experts about their relative confidence levels prior to assessing the weights for the logic-tree branches. The aim of the latter is to reduce overconfidence bias in individuals during the assessment of logic-tree weights. We reduce the power of the statistical tests of the Cooke (1991) method for the former, because we feel there is sufficient bias in the selection of calibration questions to warrant the need for strong evidence before moving away from uniform weighting of the experts.

The second step is the selection of the experts. As introduced in the previous section, we have selected experts from the NZ NSHM 2022 project team for this step, and the TAG as our overall procedure for obtaining expert judgment was a process that began at the initiation of the project and operated throughout its lifespan. We have followed the guidelines in Christophersen and Gerstenberger (2021). We have selected a range of expertise and experience to help minimize bias. Experts external to the NZ NSHM 2022 were not used, because there was not sufficient topical knowledge external to the NZ NSHM 2022 team or TAG, or the time to adequately inform any such experts; the challenge of adequately informing external experts was considered greater than any potential bias mitigation they might bring to the process. Fifteen experts participated in the SRM and nine in the GMCM.

Because of the short time available for the elicitation, the international scattering of the experts, and the challenges of conducting such a project during COVID times, the elicitation workshops were held entirely online. Because the experts were all experienced in the data, methods, and results being assessed from the multiyear working group process (see the Science working groups section), the importance and influence of the science discussions during the elicitation workshops was greatly reduced; hence, the expectation is that the bias from group dynamics was reduced when compared with elicitations in which experts are only fully informed of the details of what is being assessed only during the elicitation workshop.

Two 90 min workshops were held for the calibration questions, in which experts from SRM and GMCM were present in each group. The SRM discussions surrounding assessment of the logic-tree weights were held across a two-hour and a one-hour workshop. The GMCM session was a single workshop. Following the workshops, the experts had several days to provide their responses. Following the GMCM workshop, a second set of questions was identified related to treatment of the back-arc region (Bradley *et al.*, 2022). The experts provided weights for these options without a workshop. Experts were also asked to provide confidence bounds on their weights; exploration of this uncertainty is left for further study (see Gerstenberger *et al.*, 2016, for a related study).

It is important to note that the elicitation workshops were only the final step in the overall process of obtaining expert judgment. Two years of workshops preceded the elicitation in which proponents and opponents of models and hypotheses presented and discussed their knowledge and understanding.

THE NSHM COMPONENT MODELS AND LOGIC TREE

The development of component models of the NZ NSHM 2022 are described in overview articles for the SRM in Gerstenberger *et al.* (2022, 2024) and for the GMCM in Bradley *et al.* (2022, 2024) with all of the subcomponent models detailed in the references therein.

A 100-year forecast

There is always an inherent time component for any hazard forecast, whether that be time independent or targeting a specific time window. The determination of this time window must be cognizant of: (1) the limitations of the data used to construct models; (2) the forecast skill of the models for different time windows; and (3) time-window implications and interests for end-users.

As discussed in Gerstenberger *et al.* (2022, 2024), a common assumption of seismic hazard analyses is that they are nominally time independent. This assumption implicitly assumes that: (1) there is a true long-term earthquake occurrence rate; (2) there is sufficient data to robustly estimate this rate; (3) there are sufficient data to obtain useful estimates in the epistemic uncertainty in the mean; and (4) that, therefore, the long-term forecasts provides the most useful forecast to end-users of the seismic hazard information. Gerstenberger *et al.* (2022, 2024) argue that there is considerable uncertainty in the first three assumptions, and that no New Zealand applications of the NSHM require long-term hazard information (not to be confused with low-probability hazard information). Therefore, a 100-year time window was used for the forecast with component model choices and logic-tree weights done in this context. The NSHM does not include short-term clustering forecasts; however, the 100-year timeframe has been chosen to explicitly acknowledge that there is uncertainty in our understanding of the stationarity of earthquake occurrence and to include this uncertainty in the NZ NSHM 2022.

We note that the NSHM results are often presented using either a probability of exceedance (PoE) in 50 yr or as an annual probability of exceedance (APoE). The results are based on the 100-year forecast occurrence rate in both the cases; however, we have used them for presentation in this article, because these metrics allow for comparison with the past models and are more familiar for both the PSHA and user community.

The seismicity rate model

New Zealand sits astride a complex plate boundary, requiring modeling of earthquakes from crustal sources, and from two

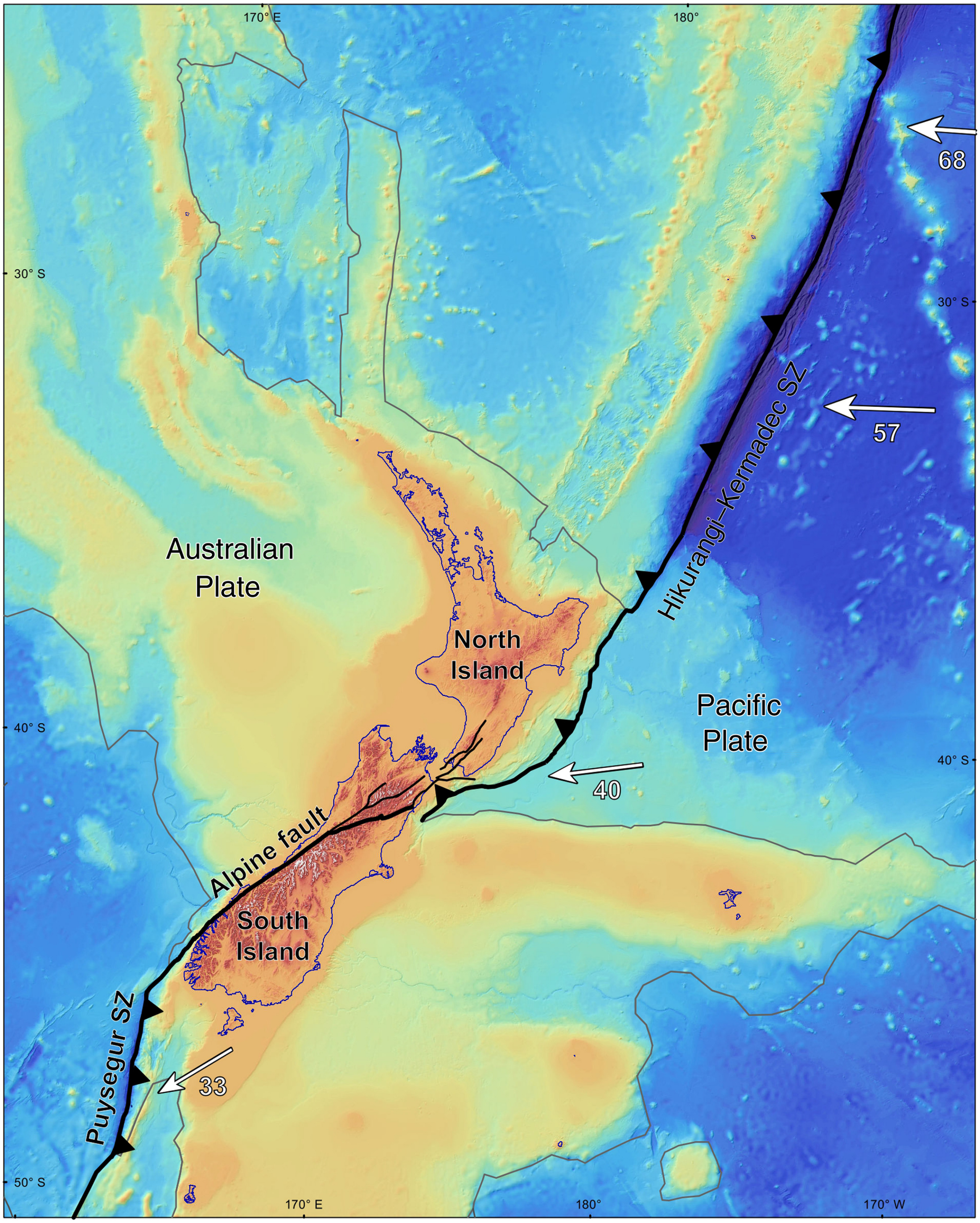

Figure 1. Tectonic setting of the New Zealand region based on Mortimer *et al.* (2020. The white arrow denotes the velocity vectors (in mm/yr) of the Pacific plate relative to the Australian plate with the vast majority of the motion between these two plates accommodated along the oppositely convergant Hikurangi–Kermadec subduction zone to the north and Puysergur subduction zone to the south, and along the Alpine fault (and other related upper-plate faults) that connects the two subduction zones. Background colors represent bathymetry and topography with the thin black line marking the approximate boundary between largely continental crust (brown and yellow colors) and mainly oceanic crust (blue colors). The color version of this figure is available only in the electronic edition.

subduction interfaces and their respective downgoing slabs (Fig. 1). For the SRM, two main component models have been developed: the inversion fault model (hereafter referred to as the inversion model) and the distributed seismicity model (hereafter referred to as the distributed model). The inversion model forecasts earthquake ruptures specifically on known faults, and the distributed model forecasts earthquake ruptures on a 0.1° × 0.1° grid across New Zealand. The inversion model is based on the UCERF3 "Grand Inversion" recipe (Field *et al.*, 2015; Gerstenberger *et al.*, 2024). In this recipe, deformation models of geologic and/or geodetic slip rate (Johnson *et al.*, 2022, 2024; Van Dissen *et al.*, 2022, 2024), data on past earthquake timings (Coffey *et al.*, 2022, 2024), and regional MFDs (Rollins *et al.*, 2022; Rollins, Christophersen, *et al.*, 2024; Rollins, Gerstenberger, *et al.*, 2024) are used to constrain rates on thousands of physically plausible ruptures (Gerstenberger *et al.*, 2022, 2024; Nicol *et al.*, 2024). These were created by linking together faults from the New Zealand CFM (Seebeck *et al.*, 2022), as described in Gerstenberger *et al.* (2024). Inversion models were developed for crustal faults ($M \geq 6.9$), and the Hikurangi–Kermadec ($M \geq 7.5$) and Puysegur ($M \geq 7.0$) subduction interfaces. These models were treated independently, and, for example, a Hikurangi–Kermadec earthquake was not modeled to rupture jointly with a crustal fault; this was done due to the short timeframe allowed for the project and the scientific communities current lack of understanding and constraints for such joint ruptures.

An important distinction from the past NZ NSHM was the increased influence of geodetic data in the SRM. These data were introduced in both the inversion model and the distributed model. For the inversion model upper-plate faults, two deformation models are developed—one using geologic-based slip rates and the other using geodetic strain-rate-based slip deficit rates. Both the models utilize the same upper-plate fault network, and both the models yield nearly identical over all moment rates (Gerstenberger *et al.*, 2024). However, there are some notable slip-rate differences and similarities between the geodetic and geologic deformation models. A notable similarity is the onshore portion of the Alpine fault where geodetic and longer term geologic rates are quite comparable. Yet, other faults show systematic differences between the rates of the geologic deformation model and the geodetic deformation model; the geodetic deformation model typical yields higher rates for low-slip-rate faults (i.e., geologic slip rates <1 mm/yr), whereas the converse is true with the geologic deformation model yielding higher rates for higher slip-rate faults. A consequence of this is that the geodetic deformation model has more moment rate in low-strain-rate regions (compared with the geologic deformation model), and the geologic deformation model has more moment rate in high-strain-rate regions. Nevertheless, based on sensitivity tests undertaken in the NZ NSHM 2022, hazard runs using the geologic-based models, and the geodetic-based models forecast similar ground-shaking hazard for cities and towns throughout the country (Gerstenberger *et al.*, 2022, 2024). Important to note here also is that overall hazard in New Zealand is not dependent just on hazard coming from the upper-plate faults, but is also dependent other factors such as hazard contributions from the subduction interfaces and the distributed seismicity model. Depending on the location and the specific hazard PoE level being considered (e.g., 10% in 50 yr, or 2% in 50 yr), any one of these factors can dominate hazard, and overwhelm changes and/or differences in the others. In the NZ NSHM 2022, both the upper-plate geologic and geodetic deformation models are weighted equally.

Differences in rates between geodetic-based and geologic estimates could have several (not mutually exclusive) explanations, such as: (1) ambiguity and trade-offs in deriving fault-specific slip deficit models for closely spaced faults; (2) errors in the geodetic modeling due to incorrect fault geometry (e.g., dip of the fault at depth, rake, and number of faults) or Earth structure (e.g., elastic heterogeneity); and (3) inaccurate fault-slip-rate estimates from geological investigations or inferences. Importantly also, some of these discrepancies might possibly result from time-dependent deformation; the geodetic-based slip deficit rates and geologic rates capture deformation rates over very different time periods, and the geodetic data may be revealing present-day rates that differ from the longer term geologic rates.

In addition, the inversion model allows for greater complexity in ruptures than was possible in the past. The 2016 M_w 7.8 Kaikoura earthquake demonstrated the need for modeling such ruptures Kaiser *et al.* (2017) and Litchfield *et al.* (2018), whereas pre-2016 earthquakes indicate that corupture of multiple faults is not unique (Beanland *et al.*, 1989; Beavan *et al.*, 2012; Nicol, Begg, *et al.*, 2022). However, a decrease in the quality of historical earthquake data with increasing time before present, and a focus on individual faults in global compilations of surface-rupturing historical and paleo earthquakes, makes it challenging to meaningfully compare our inversion results to observations (Nicol *et al.*, 2024). The inversion model includes single fault, single-fault segment, and multifault ruptures, with rupture lengths of <100 km occurring at the highest rates (Nicol *et al.*, 2024). Potential rupture scenarios are defined using plausibility filters to exclude rupture geometries that are considered geologically or dynamically unlikely (Milner *et al.*, 2013, 2022). Corupture of the two adjacent faults is considered possible when; (1) the maximum jump distance was ≤15 km; (2) the cumulative slip-rake change <360°; (3) the minimum number of subsections is greater than or equal to 2; and (4) the range of Coulomb stress thresholds are exceeded. The plausibility filters were largely adopted from UCERF3 and more recent work (Milner *et al.*, 2013, 2022). However, we increased the maximum jump distance from the 5 km in UCERF3 (Field *et al.*, 2014) to 15 km. This increase was required to allow for uncertainties in fault dips at depth, for unknown connecting faults (primarily in the subsurface), and for the incomplete mapping of fault traces (e.g., in low-strain-rate regions). Fault dips in the fault source model are primarily constrained by surface observations and assumed to be uniform to the base of the seismogenic crust. Uncertainties on the dips, which are typically ≥±10°, could impact fault separations and intersections at depth. In addition, decreasing fault dips with increasing depth, such as it has been suggested for normal faults in the Taupo rift (Villamor and Berryman, 2001) and thrust faults in Westland (Ghisetti *et al.*, 2014), could increase the likelihood of fault intersections but are not included in our model. Similarly, unknown faults at depth could promote fault connectivity in areas of thrust faulting, including Hikurangi margin, Marlborough, and West coast regions of New Zealand (Nicol, Khajavi, *et al.*, 2022). For example, the offshore splay thrust fault (OSTF) connected the southern and northern ruptures at depth in the Kaikōura earthquake, whereas these ruptures were separated by about 15 km at the ground surface. In the absence of the earthquake, the role of the OSTF as a connector structure would have been speculative in the fault source model. Finally, in low-strain areas active fault traces can be 50% or more short than their length at depth (Mouslopoulou *et al.*, 2012), and faults that intersect may be represented in the source model as unconnected structures. The 15 km jump distance produced rupture lengths of up to 1200 km; however, these long ruptures occur infrequently and are unlikely to be unambiguously identified from the paleoseismic record.

The distributed model consists of separate models for crustal, slab, and interface (Rollins *et al.*, 2021; Gerstenberger *et al.*, 2022, 2024; Thingbaijam, Gerstenberger, *et al.*, 2022; Thingbaijam *et al.*, 2024), each modeled on a 0.1° grid spacing. In addition, for the distributed model, the spatial component of the forecast has been separated from the overall rate component (see The Seismicity Rate Model section for a discussion of the occurrence rate model). Multiple models are applied for both the components. Declustering has not been applied to the overall rate component model; however, it has been applied to the spatial distribution (e.g., Marzocchi and Taroni, 2014; Gerstenberger, Marzocchi, *et al.*, 2020; Meletti *et al.*, 2021; Field *et al.*, 2022). Spatial clustering was added back in using the medium-term clustering every earthquake as a precursor according to scale model (EEPAS; Rhoades and Van Dissen, 2003; Rhoades and Evison, 2004; Rastin *et al.*, 2021, 2022).

The spatial crustal distributed model (DSM) forecasts ruptures for $5.0 \le M \le 8.0$ for the upper 40 km of the crust. A hybrid model (Rastin *et al.*, 2022) is a primary component of the crustal distributed model. This model is a multiplicative combination of three smoothed seismicity models (Frankel, 1995; Jackson and Kagan, 1999; Helmstetter and Werner, 2012), geodetic strain rate (Johnson *et al.*, 2022), and proximity to faults (Seebeck *et al.*, 2022), including a scaling based on geologic slip-rate data (Litchfield *et al.*, 2022; Seebeck *et al.*, 2022, 2023). Such models have been shown to outperform smoothed seismicity models in statistical testing (e.g., Rastin *et al.*, 2022) over five-year timeframes, and the hybrid procedure optimizes the model combination to produce the best forecast for the time window between 1951 and 2020, through independent testing of the seven 10-year periods. However, this model optimization is controlled by its performance in high-seismicity regions due to the implicit deficiency of data in lower seismicity regions; the same limitation exists for purely smoothed seismicity-based models. Finally, medium-term decadal scale clustering is added back in via the EEPAS component model, which is an additive component to the hybrid and is given a 20% weight. An example implication of this is that forecast rates in the Canterbury region are higher than the long-term average, which is consistent with the ongoing activity, which is elevated compared with the long-term average (Gerstenberger *et al.*, 2022).

A uniform rate model has been developed specifically for lower seismicity regions (Iturrieta *et al.*, 2022, 2024a). This model uses reduced spatial and temporal precision to account for the large uncertainty in these regions (Iturrieta *et al.*, 2022, 2024a). Three important parts of this component model are: (1) the development of five large uniform rate zones that are constrained by geodetic strain rates and do not use seismicity information as an input; (2) the application of a negative-binomial distribution in the hazard calculations; and (3) accounting for the bias toward a lower forecast mean as seen in lower seismicity regions in New Zealand and Japan Iturrieta *et al.* (2022, 2024a). The hybrid model and the uniform rate zone model are combined by applying the uniform model as a floor to the hybrid model.

Traditional PSHA models include a distributed model that typically has sole aim of forecasting earthquakes on faults that are not yet known about. Although the distributed model does not forecast ruptures specifically on known faults, conceptually it is not simply forecasting earthquakes for faults that we do not yet know about. It can be considered a complete rupture forecast model on its own. For this reason, we have applied a spatially weighted combination of the crustal inversion and distributed models in which the distributed model is given a weight of 0% at the locations of known (or explicitly modeled) faults for $M \ge 6.9$, and this is increased with a power law to a full weight of 100% at a distance of 12 km from faults (Gerstenberger *et al.*, 2024). This is normalized to provide an 80% weight to the inversion model (IFM) and a 20% weight to the distributed models within 12 km of faults. For $M_w < 6.9$ the DSM received effectively received a weight of 100%, and the IFM is effectively given a weight of 100% above the maximum magnitude of the DSM ($M_w > 8$). This weighting reflects the degree of belief the

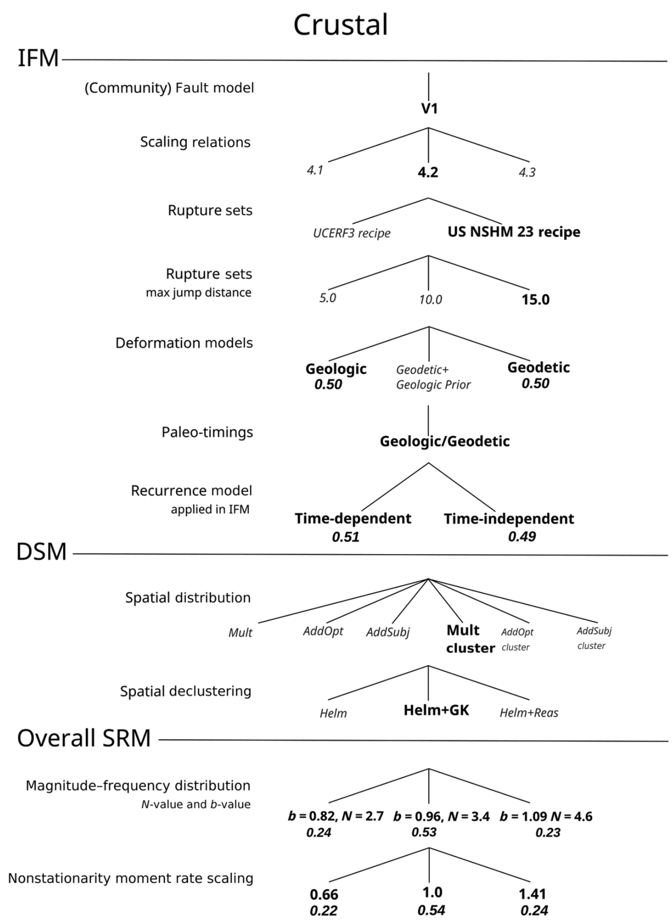

Figure 2. Crustal logic tree from the seismicity rate model (SRM). Branch options that were explored but not used in the final model are shown in gray. Branch weights are shown below the branch option in bold italic font.

modeling team had in each model; this can be contrasted with hazard models that truncate the distributed model at the minimum magnitude of the fault model, indicating a degree of belief of 0 for the distributed model for these magnitudes.

For the Hikurangi–Kermadec interface, the distributed model forecasts earthquakes of $5.0 \le M \le 7.5$ with the spatial distribution derived from a spatially normalized slip deficit rate model (Johnson *et al.*, 2022, 2024; Van Dissen *et al.*, 2022, 2024). Although the Hikurangi–Kermadec inversion model forecasts earthquakes of $M \ge 7.5$, the Puysegur inversion model forecasts earthquakes of $M \ge 7.0$; and, therefore, no distributed model was used for the Puysegur interface due to the lack of sensitivity to smaller magnitudes in this region of low population.

Thingbaijam *et al.* (2024) developed models for intraslab earthquakes in both the Hikurangi–Kermadec and Puysegur subduction zones. These models are uniform rate zone models applied to the subduction zone geometry used in the inversion model. The models use the regional moment tensor solution catalog to evaluate the orientation of finite-fault ruptures (strike subparallel to trench and dips >60°). The maximum magnitude for intraslab earthquake of 8.15 is used based on an average of historical intraslab earthquakes across the globe and on the lack of sensitivity of the hazard results to this parameter.

Rupture occurrence rate model

An occurrence rate model is the final component model of the SRM, and it was applied to both the inversion model and the distributed model. For calculating the occurrence rates, a revised earthquake catalog was developed with consistent M_w and revised depths, when possible (Rollins *et al.*, 2021; Christophersen *et al.*, 2022). The forecast of the number of $M \ge 5.0$ for 100 yr and Gutenberg–Richter b-values were developed for four regions: (1) crustal; (2) Hikurangi–Kermadec subduction interface; (3) Puysegur subduction interface; and (4) slab (i.e., seismicity in the downgoing plate below the subduction interface for both the Hikurangi–Kermadec and Puysegur subduction zones).

There is a considerable uncertainty in our understanding related to estimating: (1) the number of earthquakes that have occurred in the past; (2) the b-value of those earthquakes; and (3) , importantly, the variability in the number of earthquakes we may experience in the next 100 yr and what the past tells us about this. We, therefore, have estimated the standard error in the mean of the occurrence rate, including uncertainty in magnitude of completeness, magnitude, and due to time-window selection. We have also estimated the overdispersion of the variability in a nominal 100-year time period when compared with the variability applied when assuming Poisson (Rollins *et al.*, 2024). Finally, the variability in forecast moment rate from the variability in MFDs was compared across the tectonic regions. The subduction interface models are critical contributors to hazard, and the uncertainty in modeling these is almost certainly greater than for the crustal model due to the lack of observations (Gerstenberger *et al.*, 2022, 2024). The forecast moment rate range is approximately double for the Hikurangi–Kermadec interface than it is for the crustal model; this is considered reasonable, given the additional uncertainty and increased size of the Hikurangi–Kermadec interface. The Puysegur interface model forecasts a considerably smaller moment rate range than the crustal inversion model. This was not considered reasonable, given the increased uncertain for the interface model, and the variability in occurrence rate was scaled to match that of the crustal model.

Multiple parameter options were explored for each of the component models. Through sensitivity testing of both earthquake occurrence rate and hazard, the parameters and component model options, and hence the number of logic-tree branches, were greatly reduced (Gerstenberger *et al.*, 2022, 2024). The final logic trees and weights for each branches are shown in Figures 2 and 3.

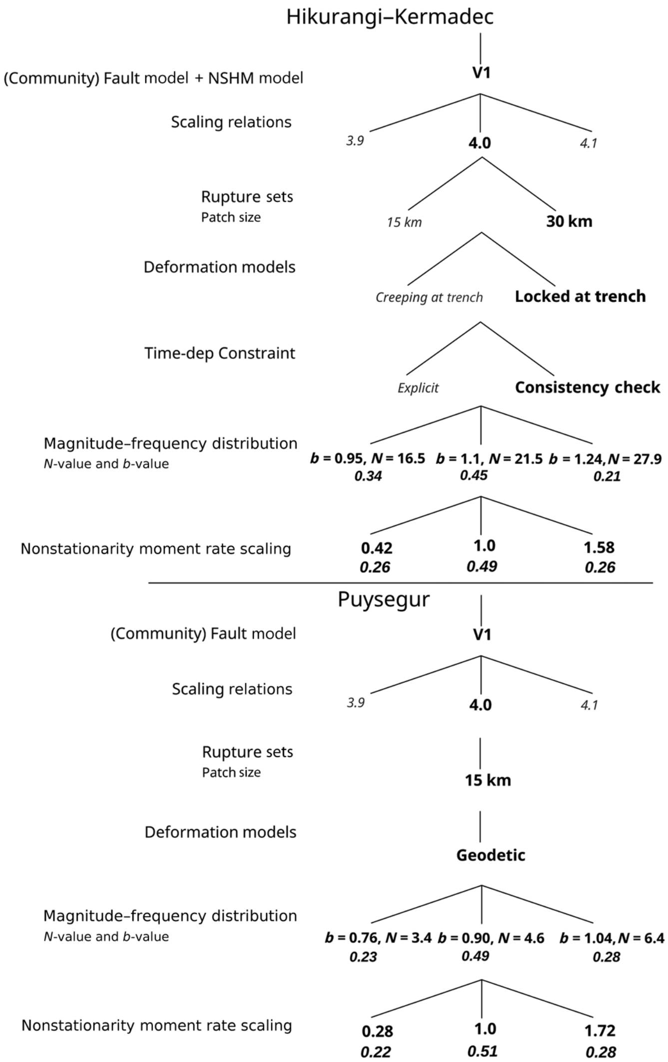

Figure 3. Interface logic tree from the SRM. Branch options that were explored but not used in the final model are shown in gray. Branch weights are shown below the branch option in bold italic font.

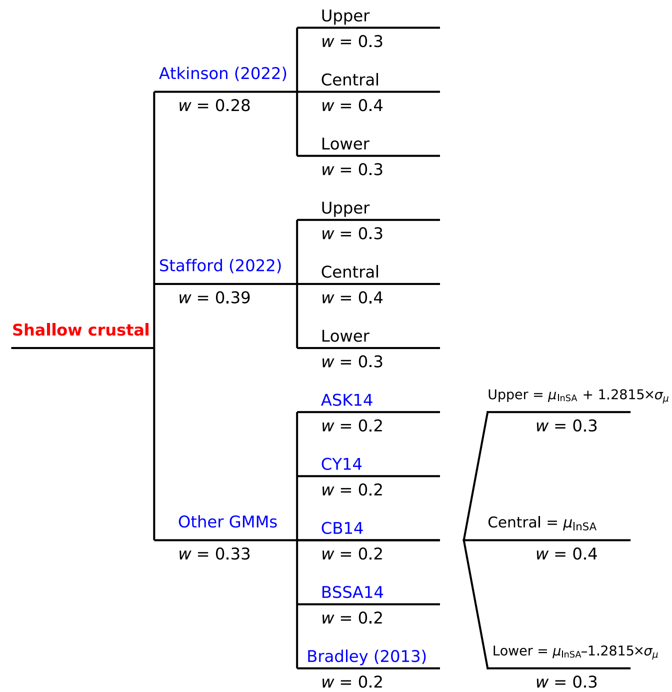

Figure 4. Crustal ground-motion characterization modeling (GMCM) logic tree used for final hazard calculations. The weights are based on expert judgments. The color version of this figure is available only in the electronic edition.

The GMCM logic tree

Update in the GMCM logic tree represents a major change in New Zealand NSHM. It involves multiple GMMs considered within a "weights on models" approach. A total of seven GMMs for crustal sources were considered with four NGAWest2 GMMs and three New Zealand adjusted GMMs. Out of the three New Zealand-adjusted GMMs, two GMMs (Atkinson, 2022; Stafford, 2022) were developed using a backbone modeling framework. For subduction interface sources, three recently derived NGA-Sub GMMs were considered along with a New Zealand adjusted backbone model of Atkinson (2022). The New Zealand-adjusted backbone GMMs were constrained using a uniformly processed and compiled database of strong-motion records (Hutchinson *et al.*, 2022) up to the end of 2021. It includes 210,809 records from 12,810 earthquakes for all source types. Thus, the epistemic branches of Stafford (2022) and Atkinson (2022) GMMs are expected to represent plausible range of epistemic uncertainty over the entire New Zealand region under the ergodic model assumption. It is worth mentioning here that the epistemic branches prescribed by the two backbone GMMs assume a perfect correlation between ground motions from different ruptures (e.g., all ruptures jointly exhibit the higher bound or lower bound for a hazard calculation). In reality, the correlation may vary as a function of magnitude, distance, and oscillator period. Essentially, the epistemic bounds maybe overestimated for some of the rupture scenarios. Thus, as a first-order correction, an average fractional reduction of 0.9 was applied to the epistemic branches of both the backbone GMMs for all ruptures and oscillator periods (Bradley *et al.*, 2024, in this volume). The value of 0.9 was estimated post hoc based on a correlation analysis of alternative NGA-West2 models for a range of magnitude and source-to-site distances (Bradley *et al.*, 2022) to account for the reduction in the range of these epistemic branches if the correlations between mean ground motions had been accounted for.

Moreover, initial evaluation and testing of various candidate GMMs was also carried out using the same database as detailed in Lee *et al.* (2022, 2024). In addition, extensive comparisons were performed between candidate GMMs and observations including data from global datasets such as

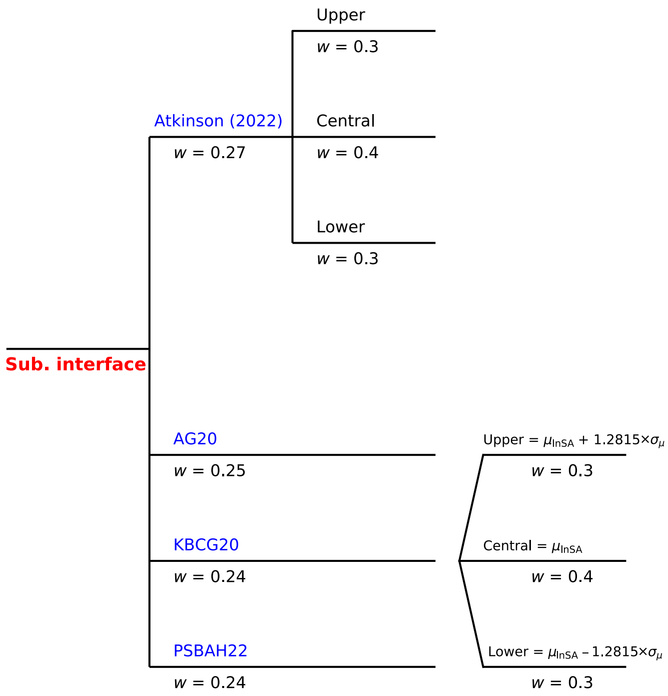

Figure 5. Subduction interface GMCM logic tree used for final hazard calculations. The weights are based on expert judgments. The color version of this figure is available only in the electronic edition.

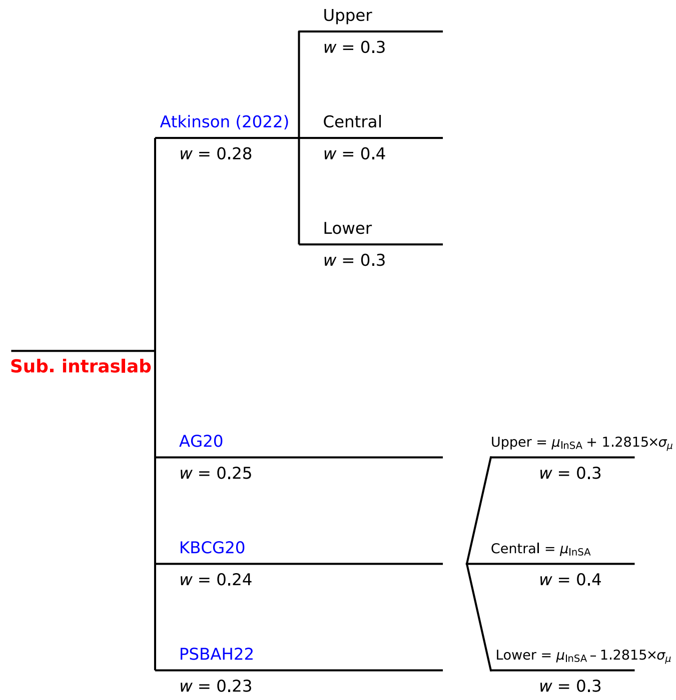

Figure 6. Subduction intraslab GMCM logic tree used for final hazard calculations. The weights are based on expert judgments. The color version of this figure is available only in the electronic edition.

NGA-Sub database for the scenarios that are relevant for hazard in New Zealand (Bradley *et al.*, 2022, 2024). Near-fault directivity effects were not considered explicitly in the median models of the GMMs but through residual distributions, that is, σ models. Two New Zealand-specific corrections were made to account for: (1) stronger back-arc attenuation in the median subduction intraslab GMMs; and (2) lower σ to account for nonlinear soil response toward softer site conditions in the median models of Kuehn *et al.* (2020), Atkinson (2022), and Parker *et al.* (2022).

The GMCM logic trees for crustal, subduction interface, and subduction intraslab sources are shown in Figures 4–6, respectively. The associated branch weights were based on expert judgments. Various comparison plots of median and σ models along with hazard sensitivities presented in accompanying articles (Bora *et al.*, 2024; Bradley *et al.*, 2024) were made available to experts prior to the expert elicitation workshop. The weights on the second level of branching (for each GMM), which essentially represent 10th (lower), 50th (central), and 90th (upper) percentiles of a lognormal distribution, were fixed to 0.3, 0.4, and 0.3, respectively. As can be observed from these figures, identical weights were applied for all oscillator periods and all considered ruptures. The additional epistemic branches were added to the NGA-West2 and Bradley (2013) GMMs in which the uncertainty in median (σ_μ) is based on number of events available in selected magnitude and distance bins of New Zealand strong-motion database compiled within the NSHM revision. The σ_μ for NGA-Sub GMMs were prescribed by the model developers. To keep parity with the backbone GMMs, the upper and lower epistemic branches for other GMMs were also chosen to represent the 10th and 90th percentiles of a lognormal distribution. For hazard computations, a 4σ truncation is used for all the GMMs.

All the GMMs used in the updated GMCM, model site effects using V_{S30}. It resulted in a significant change from conventional New Zealand-specific site subsoil class (used in previous NSHMs (Standards New Zealand, 2004; McVerry *et al.*, 2006) to V_{S30}-based site characterization. The basin effects are implicitly included through generic $V_{S30} - Z_1$ (depth to 1 km/s shear-wave velocity horizon) and $V_{S30} - Z_{2.5}$ (depth to 2.5 km/s shear-wave velocity horizon) correlations in NGA-West2 GMMs. We would also like to note that there are ongoing efforts to better characterize site effects in major basins across New Zealand such as Wellington and how to incorporate them to NZ NSHM (Kaiser *et al.*, 2022, 2024).

HAZARD RESULTS

Forecast hazard maps for 10% and 2% PoE in 50 yr for peak ground acceleration (PGA) and $V_{S30} = 250$ m/s are shown in Figures 7 and 8. Figures 9–12 show the equivalent figures for spectral acceleration, SA(1 s) and SA(3 s). Hazard curves are shown for Auckland (Fig. 13), Wellington (Fig. 14),

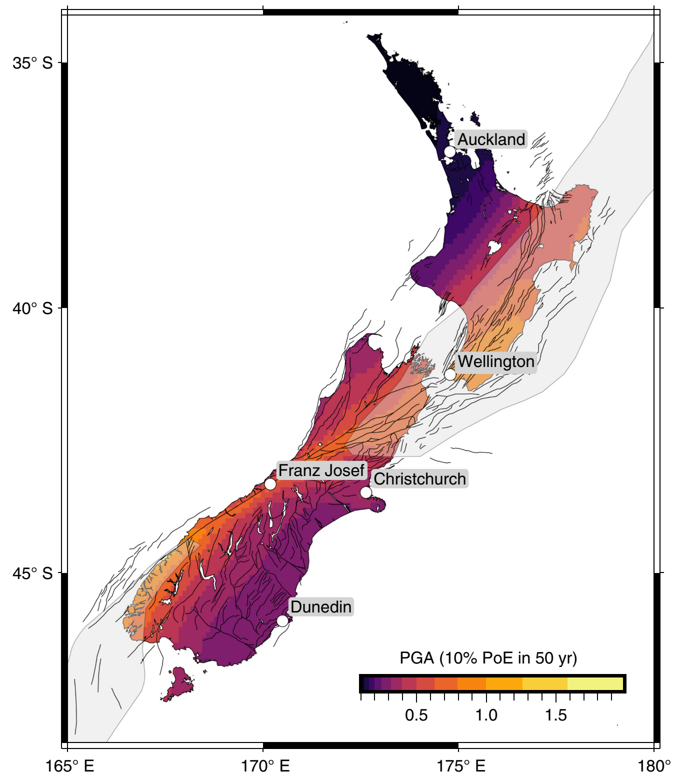

Figure 7. Peak ground acceleration (PGA) with a 10% probability of exceedance (PoE) in 50 yr and $V_{S30} = 250$ m/s. Labeled locations correspond to population centers referred to in text and figures. Also shown is New Zealand National Hazard Seismic Model (NZ NSHM) 2022 fault model. The color version of this figure is available only in the electronic edition.

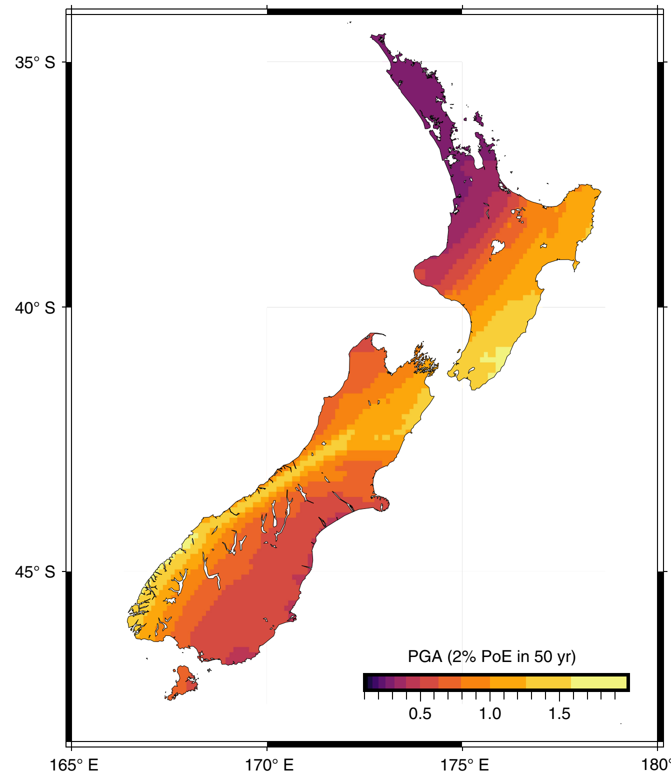

Figure 8. PGA with a 2% PoE in 50 yr and $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

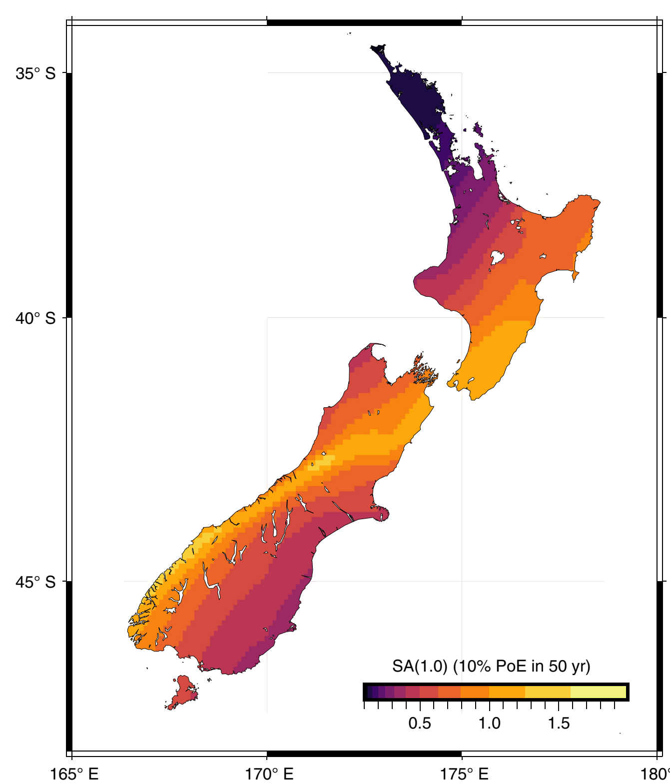

Figure 9. Spectral acceleration, SA(1 s) with a 10% PoE in 50 yr and $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

Christchurch (Fig. 15), Franz Josef (Fig. 16), and Dunedin (Fig. 17). For each curve, the 10th percentile and the 90th percentile curves are shown.

Disaggregations for PGA at 10% probability in 50 yr are shown for $V_{S30} = 400$ m/s for Auckland (Fig. 18) and Wellington (Fig. 19).

For Wellington, Figure 20 shows the variability in shape of the hazard curves based on V_{S30} for PGA and SA(1.0 s). A change in shape is particularly noticeable for PGA in which higher V_{S30} values result in flatter hazard curves.

Comparison to the previous NZ NSHM 2010

As described in the previous sections, the NZ NSHM 2022 included fundamental revisions of all model components, including the development of an extensive logic tree for modeling epistemic uncertainty. This represents a significant departure from the past New Zealand models, which included no epistemic uncertainty (Stirling *et al.*, 2012). In all comparisons we show the single 2010 hazard curve and the mean and the 10th and 90th percentile hazard curves from the NZ NSHM 2022. It is necessary to provide the distribution of PoEs from the NZ NSHM 2022, because, as in the unified framework developed in Marzocchi and Jordan

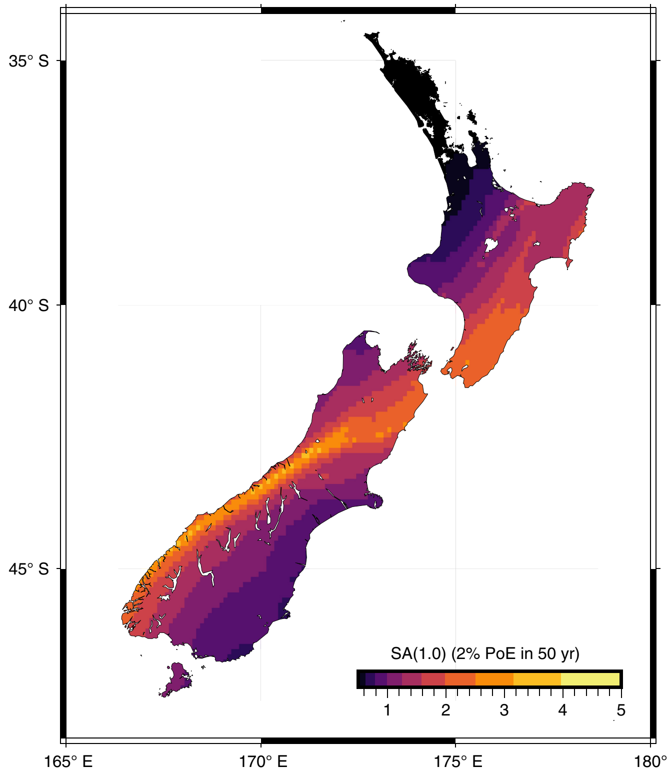

Figure 10. SA(1 s) with a 2% PoE in 50 yr and $V_{S30} = 250$ m/s. Note the color scale change compared with most of the other figures depicted here so far. The color version of this figure is available only in the electronic edition.

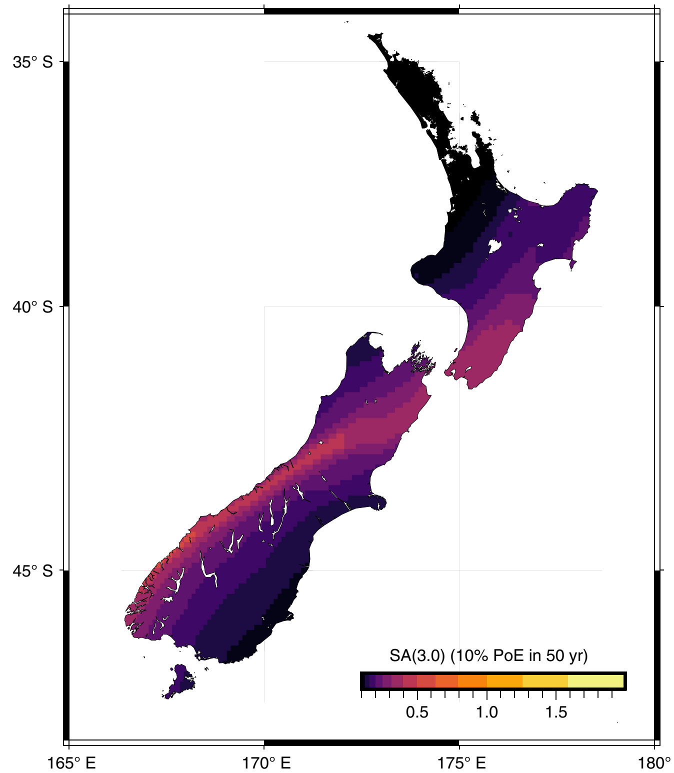

Figure 11. SA(1 s) with a 10% PoE in 50 yr and $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

(2014, 2017), the PoE is described by a distribution and is not a single number. In addition, providing the full distribution allows the confidence the NSHM team had in any single forecast metric to be transparent to any users of the forecasts.

Figures 13–17 also show the comparison of the NSHM 2010 hazard curve for each major location with that of the NSHM 2022 with the 80% confidence bounds. The NSHM 2010 did not include epistemic uncertainty in the model. For these locations, it can be seen that the "best estimate" hazard curve from the NSHM 2010 generally falls around or below the 10th percentile curve of the 2022 model. Exceptions to this can be seen for high-probability shaking in which the NSHM 2010 can exceed the 90th percentile curve of the NSHM 2022.

For a more systematic spatial comparison, ratio maps of various intensity metrics are shown. All ratio maps are for $V_{S30} = 250\,\mathrm{m/s}$. Figure 21 is PGA with a 10% PoE in 50 yr; Figure 22 is PGA with a 2% PoE in 50 yr; Figure 23 is SA(1.0 s) with a 10% PoE in 50 yr; and, finally, Figure 24 is SA(1.0 s) with a 2% PoE in 50 yr. Other maps are not shown, as generally the observations from the maps shown hold for other metrics. Comprehensive results can be seen using the NZ NSHM 2022 web tools.

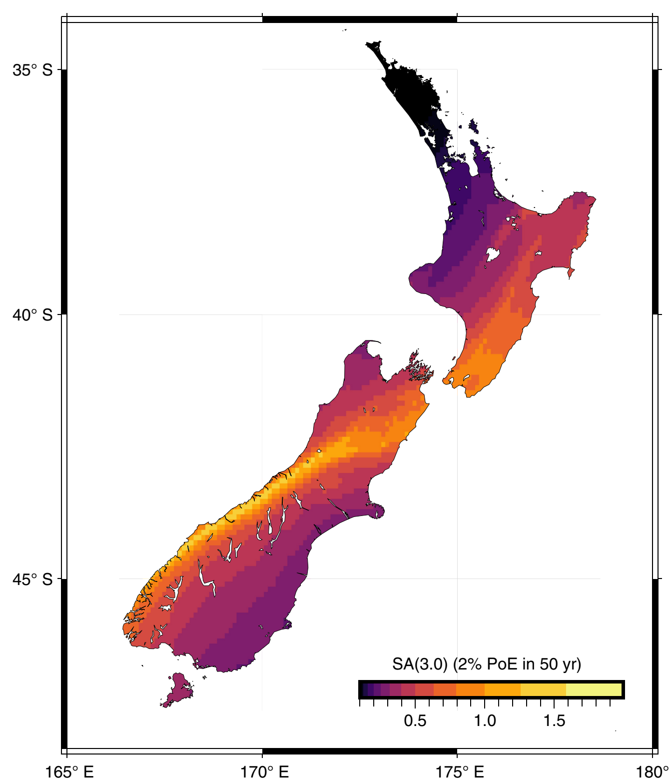

Figure 12. SA(1 s) with a 2% PoE in 50 yr and $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

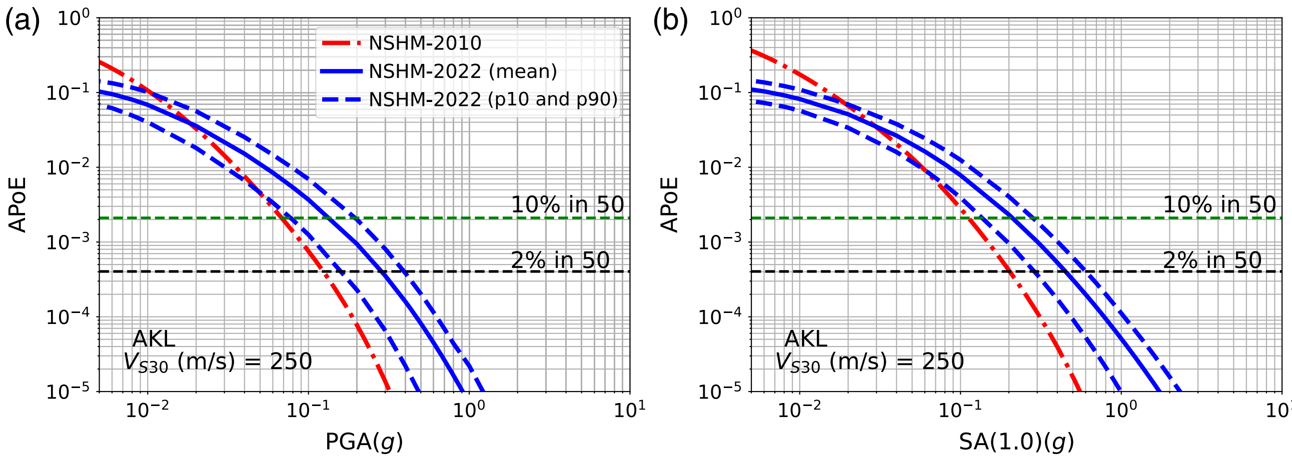

Figure 13. Hazard curves for Auckland. Plotted as the annual probability of exceedance (APoE). (a) PGA and (b) SA(1.0). The blue dashed lines indicates the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

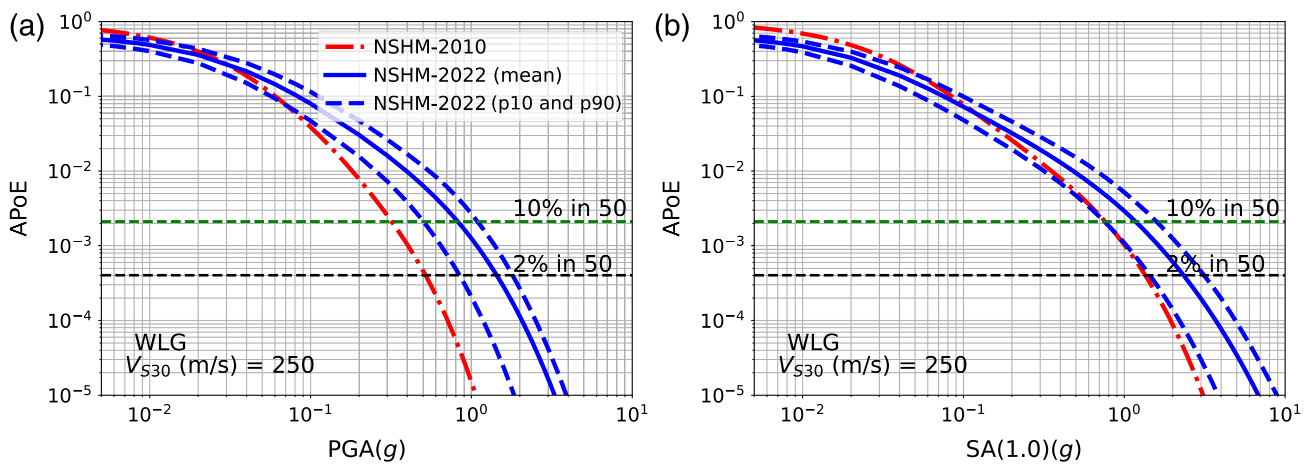

Figure 14. Hazard curves for Wellington. Plotted as the APoE. (a) PGA and (b) SA(1.0). The blue dashed lines indicate the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

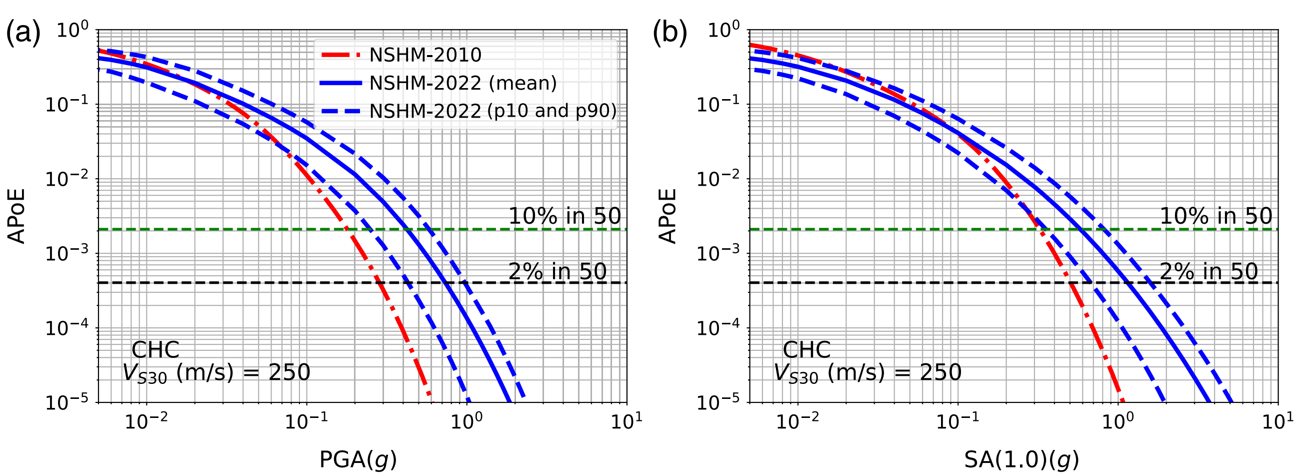

Figure 15. Hazard curves for Christchurch. Plotted as the APoE. (a) PGA and (b) SA(1.0). The blue dashed lines indicate the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

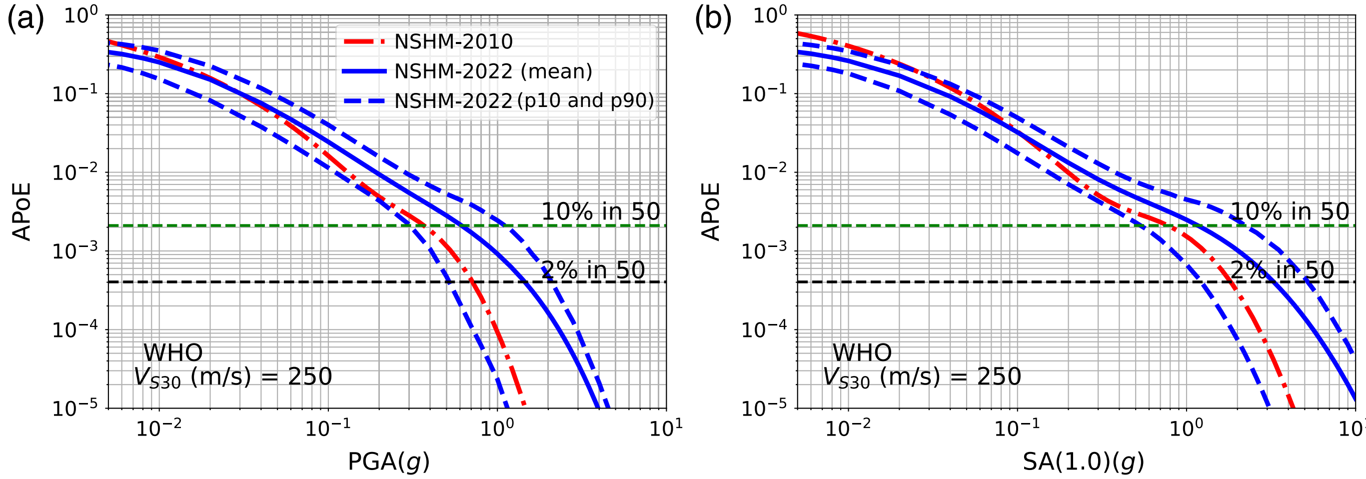

Figure 16. Hazard curves for Franz Josef. Plotted as the APoE. (a) PGA and (b) SA(1.0). The blue dashed lines indicate the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

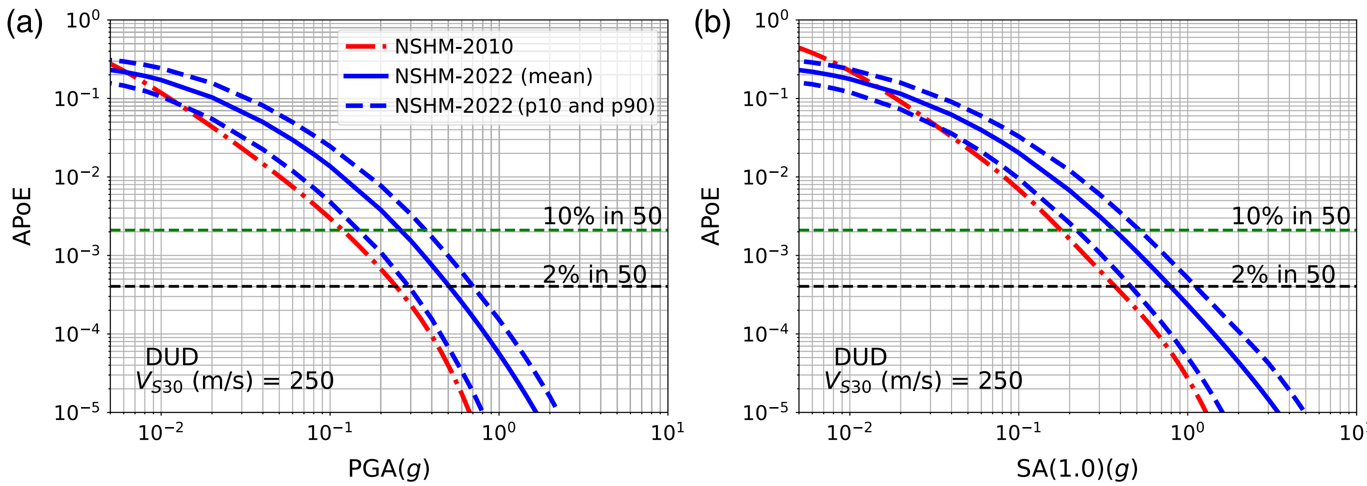

Figure 17. Hazard curves for Dunedin. Plotted as the APoE. (a) PGA and (b) SA(1.0). The blue dashed lines indicate the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

Model components with the greatest impact on the calculated hazard changes

To understand what model components are controlling the observed increases in calculated hazard, we have broken down the 2010 and 2022 NSHMs into their own SRM and GMCM components. By combining, for example, the 2010 SRM with the 2022 GMCM, we are able to understand if the SRM or GMCM is contributing the most to the observed hazard changes. Figure 25 shows the various component model permutations for Wellington, and Figure 26 shows the same permutations for Auckland. For Wellington, it can be observed for PGA and SA(1.0 s) and for $V_{S30} = 250$ m/s and 400 m/s that the results are very similar to those of the full 2022 NSHM when combining the 2010 SRM with the 2022 GMCM. This demonstrates that the calculated hazard increases are mostly coming from changes to the GMCM for Wellington. The changes from the SRM are not negligible; however, they are most evident for higher probability shaking. For Auckland, we see the reverse, and the SRM is creating more of the calculated hazard increase. It can be observed that the 2022 SRM, when combined with the 2010 GMCM, results in hazard that is equivalent to or exceeds the 2022 NSHM, whereas the 2010 SRM when combined with the 2022 GMCM produces lower hazard. The change in the spectral

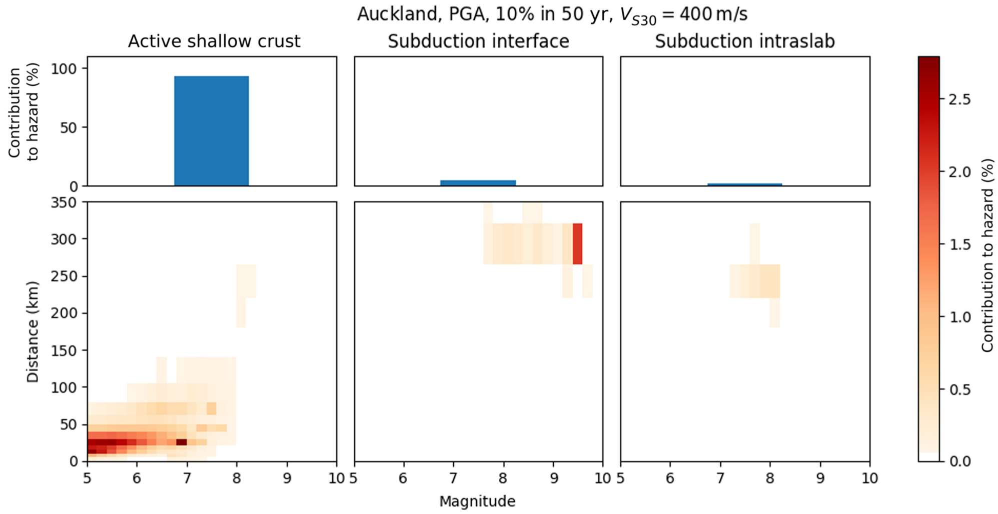

Figure 18. Disaggregation for seismic hazard at Auckland for PGA, 10% probability in 50 yr. Bars in top row show total contribution to hazard of each tectonic region type (TRT). 2D color maps in bottom row show disaggregation by magnitude and distance for each TRT. The color version of this figure is available only in the electronic edition.

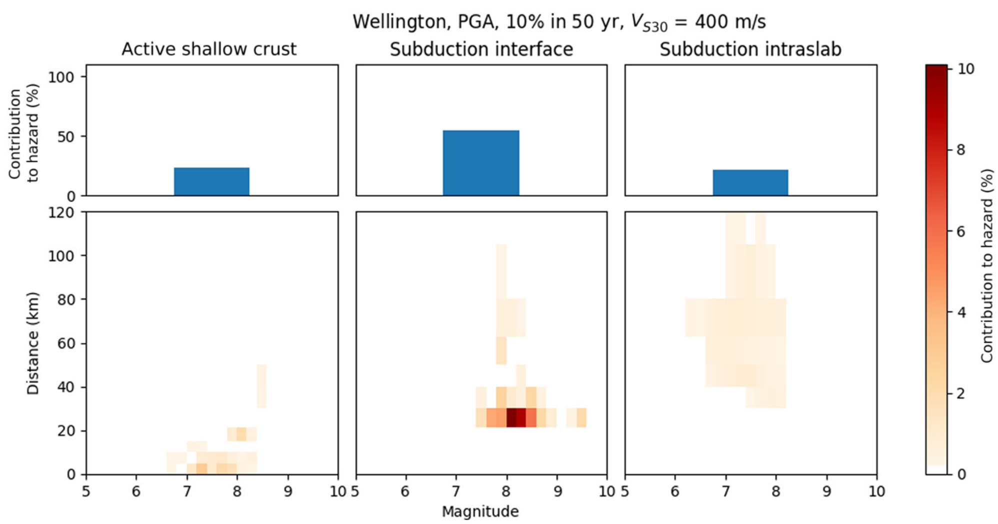

Figure 19. As Figure 18 for Wellington PGA, 10% probability in 50 yr. The color version of this figure is available only in the electronic edition.

shape from the 2010 NSHM is also apparent in these figures with the largest increases seen for PGA (and shorter periods not shown here).

Tornado plots and additional hazard sensitivity analysis. Sensitivity analysis were performed throughout multiple stages of the NZ NSHM 2022 (Bradley *et al.*, 2022, 2024; Gerstenberger *et al.*, 2022, 2024). For the SRM, such analysis was done on both the occurrence rate outputs and the final hazard results. GMCM analysis were performed against the observational data and the final hazard results (Bora *et al.*, 2024). In this section we discuss the hazard sensitivity testing.

Sensitivity of hazard to the branches of the crustal and Hikurangi–Kermadec subduction interface SRM logic-tree branches is shown in Figures 27 and 28. For simplicity, we have excluded branches of the Puysegur subduction interface logic tree, though similar conclusions can be drawn about the *N*-scaling branches for that logic tree. The influence of a particular branch set (e.g., crustal *N*-scaling or Hikurangi–Kermadec MFD *b*-value) is calculated as the change in exceedance rate from the central branch to the outer branches normalized by the mean exceedance rate for the complete model. In cases in which there are only two logic-tree branches (e.g., crustal deformation model), the change in rate is calculated from the mean of the two branches rather than a central branch.

The sensitivity calculation was performed for a range of PGA values (0.1*g*, 0.5*g*, and 1.0*g*). In Figure 27, we show the mean hazard sensitivity for all points in New Zealand over a 0.2° grid. Crustal *N*-scaling has the largest effect followed by Hikurangi–Kermadec *N*-scaling, and then *b*-value for Hikruangi–Kermadec and crustal ruptures. Sign of the hazard increase due to the crustal *b*-value depends on the level of shaking, that is, higher hazard is produced by the higher *b*-value at low PGA but by the lower *b*-value at high PGA, reflecting the relative rate of small and large earthquakes for different *b*-values. In addition, the influence of the branches lower on the diagram (e.g., time dependence and crustal deformation model) increases as PGA increases (i.e., for low PoEs).

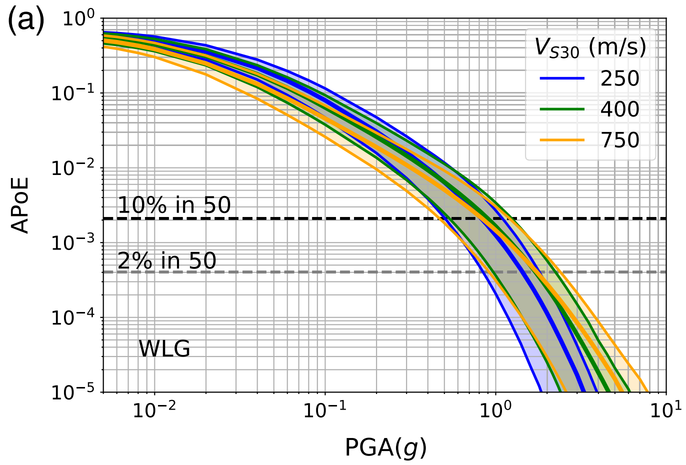

Figure 20. Hazard curves for Wellington, showing the variability in shape with V_{S30}. Plotted as the APoE. (a) PGA and (b) SA(1.0). Colored shaded regions indicate the bounds of the 10th and 90th percentiles. The color version of this figure is available only in the electronic edition.

To show the change in sensitivity for different locations, we have calculated hazard sensitivity at the individual sites for Auckland, Wellington, and Franz Josef (Fig. 28). The influence of the time-dependent rate adjustment on the Alpine fault is clearly seen at Franz Josef.

Figures 29 and 30 show comparisons of the variability introduced by different components between the NZ NSHM 2022 and the NZ NSHM 2010 GMCMs for two example cities: Auckland and Wellington. These figures primarily show changes in calculated hazard due to the changes between GMCM 2010 and GMCM 2022 using SRM 2010 as the source characterization model. Then these changes are compared with the changes caused by SRM changes (i.e., SRM 2010 to SRM 2022). Also shown are the relative changes introduced by

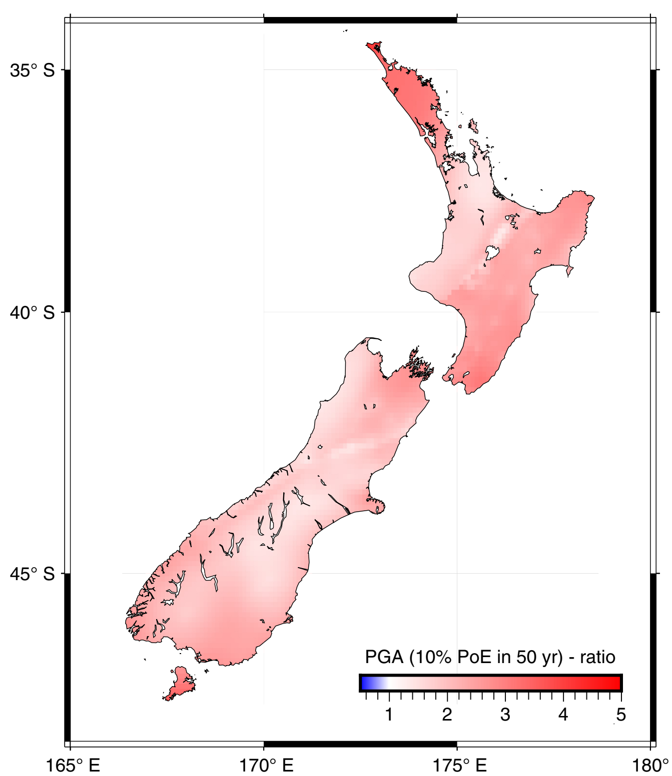

Figure 21. Ratio map of the NZ NSHM 2022 10% PoE in 50 yr PGA hazard map to the same for the 2010 NSHM with $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

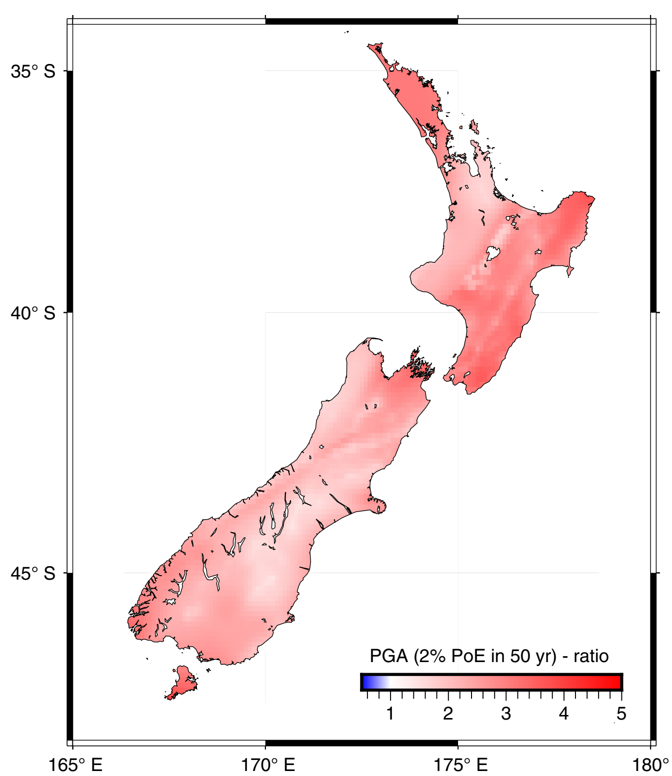

Figure 22. Ratio map of the 2022 NSHM 2% PoE in 50 yr PGA hazard map to the same for the 2010 NSHM with $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

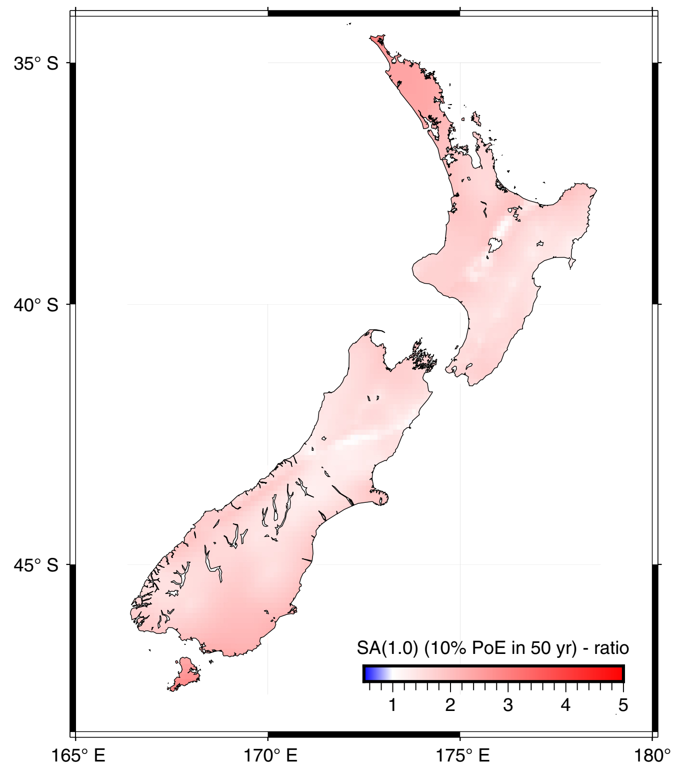

Figure 23. Ratio map of the 2022 NSHM 10% PoE in 50 yr SA(1.0 s) hazard map to the same for the 2010 NSHM with $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

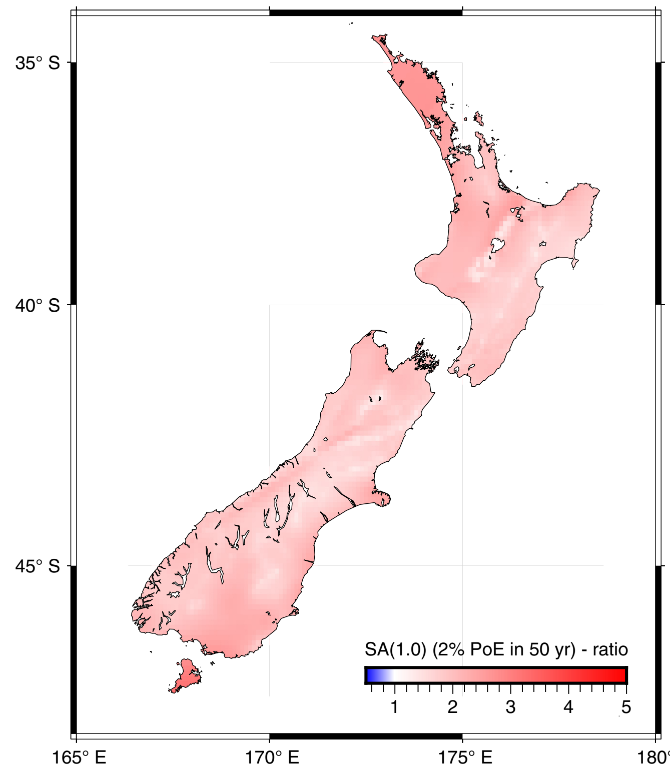

Figure 24. Ratio map of the 2022 NSHM 2% PoE in 50 yr SA(1.0 s) hazard map to the same for the 2010 NSHM with $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

GMMs based on tectonic type. Majors observations that can be made from these figures are: (1) change in GMCM from NSHM 2010 to NZ NSHM 2022 accounts for the major change in calculated hazard in high-hazard regions such as Wellington. In low-hazard regions (e.g., Auckland) the change in SRMs (SRM 2010 to SRM 2022) is the dominant effect with this predominantly controlled by increases introduced via the uniform rate zone model; (2) Within GMCM-2022, the change in crustal GMMs (from NSHM 2010 to NZ NSHM 2022) accounts for the major change both in Auckland and Wellington, whereas the change in interface GMMs have a compounding effect for Wellington; and (3) for all cities investigated, the difference between logic-tree weighting schemes was negligible for the 2022 GMCM. For most of the cities, the noticeable features are the dominance of the changes in crustal and interface models, and the near parity of change introduced by the SRM and GMCM.

Comparison of hazard forecasts against observed shaking data

Stirling *et al.* (2022, 2023) tested the NZ NSHM 2022 forecast ground-motion exceedance rates against the observed exceedance rates for strong-motion stations around New Zealand. Because of limited exceedances of large-shaking thresholds, the testing was done for exceedances of 0.1*g* and 0.2*g*, and the epistemic uncertainty was modeled by assuming a Binomial distribution (Marzocchi and Jordan, 2018). Stirling *et al.* (2022, 2023) consider the full epistemic uncertainty distribution by developing a weighted combination of the Binomial distribution for each branch in the logic tree. They found that in most cases the observed exceedance rates were consistent with the NZ NSHM 2022 forecasts, and that discrepancies were related to major earthquake sequences (e.g. Christchurch) that are not explicitly modeled in the NZ NSHM 2022 forecast. Because of the limited number observations only cautious conclusions can be drawn from this result, and more work is necessary to better understand how to test seismic hazard forecasts.

DISCUSSION AND CONCLUSIONS

The NZ NSHM 2022 is a fundamental revision of nearly all components of prior NSHMs in New Zealand. In general, over most of the New Zealand and for most hazard metrics, the NZ NSHM 2022 forecasts increased hazard when compared with the 2010 NSHM. The exact quantum of increase is highly variable and depends on the hazard metric concerned, but can range from roughly 0 to a factor of more than three times. The change from New Zealand site subsoil class to V_{S30} is

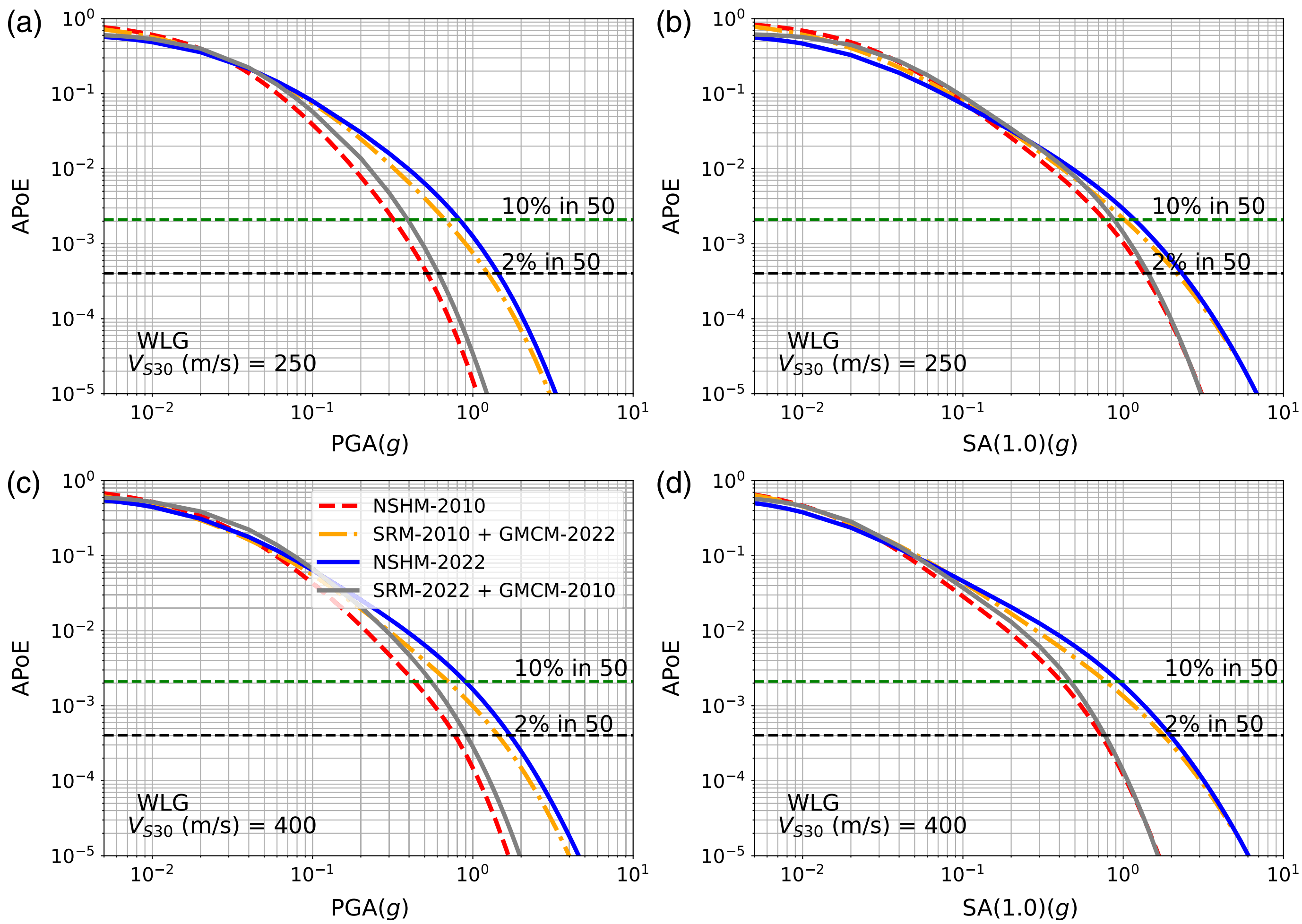

Figure 25. Comparisons of hazard curves for Wellington to show differences between 2010 and 2022 NSHM components. Shown are the 2022 NSHM, the 2010 NSHN, the 2010 SRM + 2022 GMCM, and the 2022 SRM + 2010 GMCM. The similarities of the 2022 NSHM and the 2010 SRM + 2022 GMCM indicate that most of the hazard changes in Wellington come from the 2022 GMCM. All are plotted as the APoE. (a) PGA and $V_{S30} = 250$ m/s; (b) SA(1.0 s) and $V_{S30} = 250$ m/s; (c) PGA and $V_{S30} = 400$ m/s; and (d) SA(1.0 s) and $V_{S30} = 400$ m/s. The color version of this figure is available only in the electronic edition.

an important complicating factor to this increase; for example, within the small area of the Wellington central business district, in locations where both V_{S30} and New Zealand site subsoil classes are constrained, the range of increase in calculated hazard reflects that seen across the entire country with factors of increase between 1 and 3.

In higher seismicity regions the increases are dominated by the changes to the GMCM (Bradley *et al.*, 2022, 2024; Bora *et al.*, 2024). The drivers of change include the inclusion of epistemic uncertainty via the use of multiple GMMs that are constrained based on modern data. There is significant epistemic uncertainty for large near-source shaking; the range of models used all represent credible forecasts calibrated on the observed data and our understanding of earthquakes physics (Bradley *et al.*, 2022, 2024). This leads to increased mean predictions and changes in spectral shape based on generally larger differences at shorter periods and increasingly less difference at longer periods. A key factor in the changes when compared with the 2010 NSHM is the bias of the McVerry *et al.* (2006) GMM with respect to the updated ground-motion database (e.g., Lee *et al.*, 2022, 2024). The McVerry *et al.* (2006) model significantly underestimates the mean for most ground-motion parameters.

The impact of aleatory uncertainty (σ) on hazard is a second-order effect; however, it is not insignificant for lower APoEs. The σ associated with NGA-Sub GMMs is in general larger than that with McVerry *et al.* (2006) and Bradley *et al.* (2024). Thus, increase in hazard can also be attributed to the larger σ depending upon the dominant source type.

Changes in the SRM also contribute appreciably in almost all locations, with larger contributions in low-seismicity areas, where models have been specifically applied in these regions to better address both the spatial and rate uncertainty in seismic activity. Interestingly the application of the negative binomial for these zones reduces the calculated hazard compared with

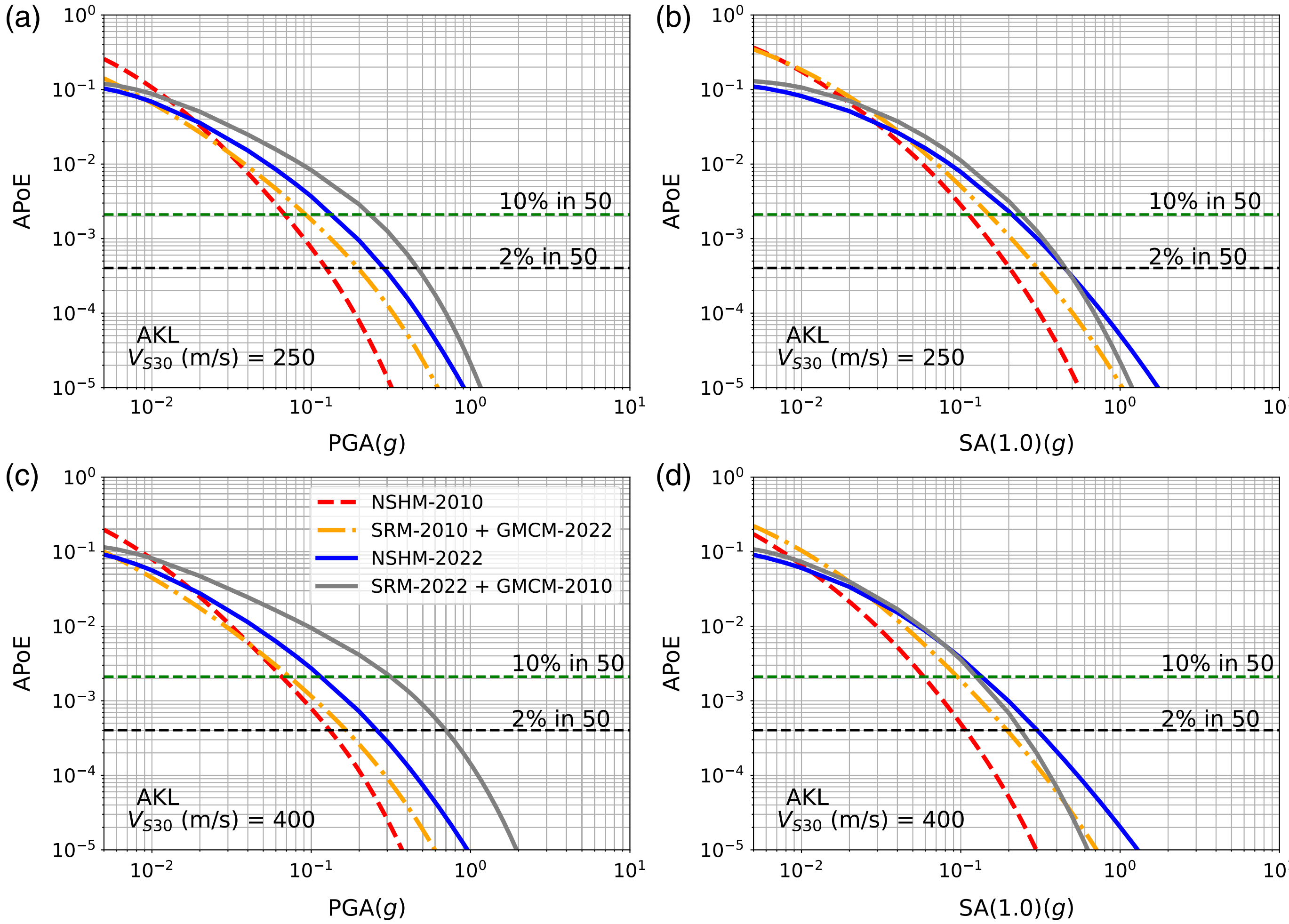

Figure 26. Comparisons of hazard curves for Auckland to show differences between 2010 and 2022 NSHM components. Shown are the 2022 NSHM, the 2010 NSHN, the 2010 SRM + 2022 GMCM, and the 2022 SRM + 2010 GMCM. The similarities of the 2022 NSHM and the 2022 SRM + 2010 GMCM indicate that most of the hazard changes in Auckland come from the 2022 SRM. All are plotted as the APoE. (a) PGA and $V_{S30} = 250$ m/s; (b) SA(1.0 s) and $V_{S30} = 250$ m/s; (c) PGA and $V_{S30} = 400$ m/s; and (d) SA(1.0 s) and $V_{S30} = 400$ m/s. The color version of this figure is available only in the electronic edition.

using a Poisson distribution (see Field *et al.*, 2022; Michael and Llenos, 2022, for related discussions); however, this is counteracted by the increase in rates from the observed bias in the mean occurrence rate (Iturrieta *et al.*, 2022, 2024a), which results in an increase in calculated hazard.

An important contributor to the epistemic uncertainty in the calculated hazard comes from *N*-scaling branches in the logic tree (e.g., Fig. 27). As discussed in the Rupture occurrence rate model section, these branches represent the uncertainty in our understanding of how many earthquakes may occur, or what the variability in moment rate may be, within the next 100 yr. The mean of this value, the uncertainty in the mean, and the variability in the range of future values are challenging to constrain and are not typically a significant focus in hazard studies.

Another observation from comparisons with the NSHM 2010 is the general "flattening" of the hazard curve (i.e., ground-motion intensity versus rate of exceedance) for most of the country. This indicates that ground motions with lower PoE (e.g., 2% PoE in 50 yr) generally increases more than ground motions with higher PoE (e.g., 10% in 50 yr) when compared with the previous NSHMs. Again, both changes to SRM and GMCM contribute to this, but with the largest contribution coming from changes to the standard deviation modeling in the GMCM. SRM changes are related to the large range in rate variability considered.

Another notable contributor to calculated hazard increases, relative to NSHM 2010, is from the SRM and GMCM modeling of the Hikurangi–Kermadec subduction zone. The impact of the change in spectral shape can be seen for the interface. For example, in the PGA hazard forecast for Wellington, the Hikurangi–Kermadec interface dominates the source contributions; however, the local crustal faults become increasingly important contributors as spectral periods increase. This illustrates the trade-offs between the very near proximity of the Wellington fault, the impact of the distance scaling in the GMCM for the interface at a distance of 25 km, and the change in spectral shape of modern GMMs when compared with the NSHM 2010.

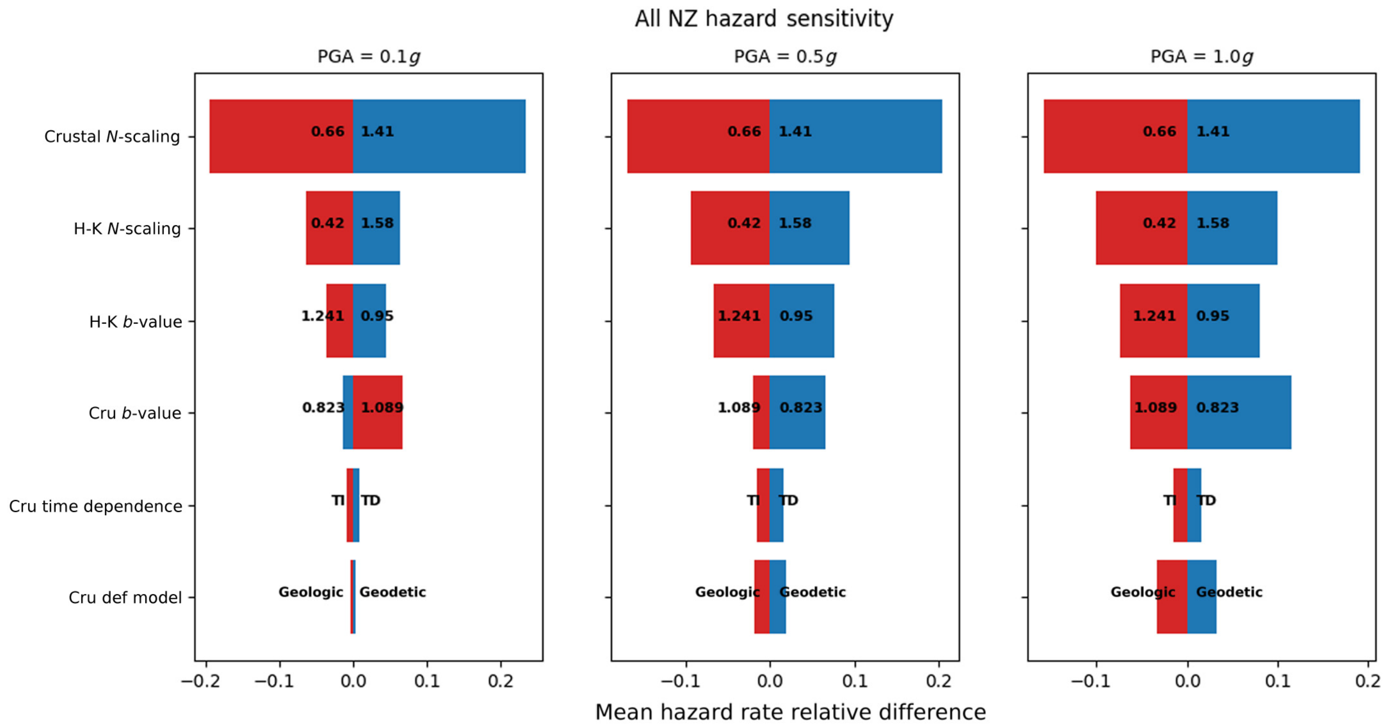

Figure 27. Hazard sensitivity tornado chart for all of New Zealand. Hazard sensitivity to SRM logic-tree branches is calculated as the change in exceedance rate from the central branch (or mean of two branches when only two are present) to the outer branches of the logic tree normalized by the rate from the complete model. The sensitivity is calculated over a 0.2° grid of New Zealand, and the mean is shown here. H-K is the Hikurangi–Kermadec subduction interface; *b*-value is the GR *b*-value for the MFD; TI is time independent; and TD is time dependent. The color version of this figure is available only in the electronic edition.

There has been a large effort to quantify and model the epistemic uncertainty in our knowledge of earthquake occurrence and shaking for both the SRM and GMCM, respectively. This leads to not only improved forecasts of the mean calculated hazard with likely greater quantitative stability but also quantification of the uncertainty ranges on the estimated hazard. More comprehensive quantification of epistemic uncertainty in seismic hazard is a topic requiring significant research and improvement in the future; however, the confidence intervals in the NZ NSHM 2022 provide the NSHM team's best present estimate of the hazard and can be used to provide guidance of the confidence in results for users of the model. Gerstenberger *et al.* (2022, 2024) and Bradley *et al.* (2022, 2024) provide discussions of recommended future work to improve hazard modeling in New Zealand, with relevance to hazard modeling around the world.

Another change from previous NZ NSHMs is the openness and availability of the NZ NSHM 2022 and its results. All model components are openly available so that results may be reproduced in the OpenQuake engine. A full suite of hazard results are available online using the NSHM web application. Hazard maps and location-specific hazard curves, uniform hazard spectra (UHS), and hazard disaggregations are available on the app, as well as other tools to explore different components of the SRM can be found there.

DATA AND RESOURCES

All data used in this article came from published sources listed in the references, except the final hazard calculations. All hazard data can be found at nshm.gns.cri.nz. The other relevant data to this article were available at https://nshm.gns.cri.nz/Resources/ScienceReports. All websites were last accessed in November 2023.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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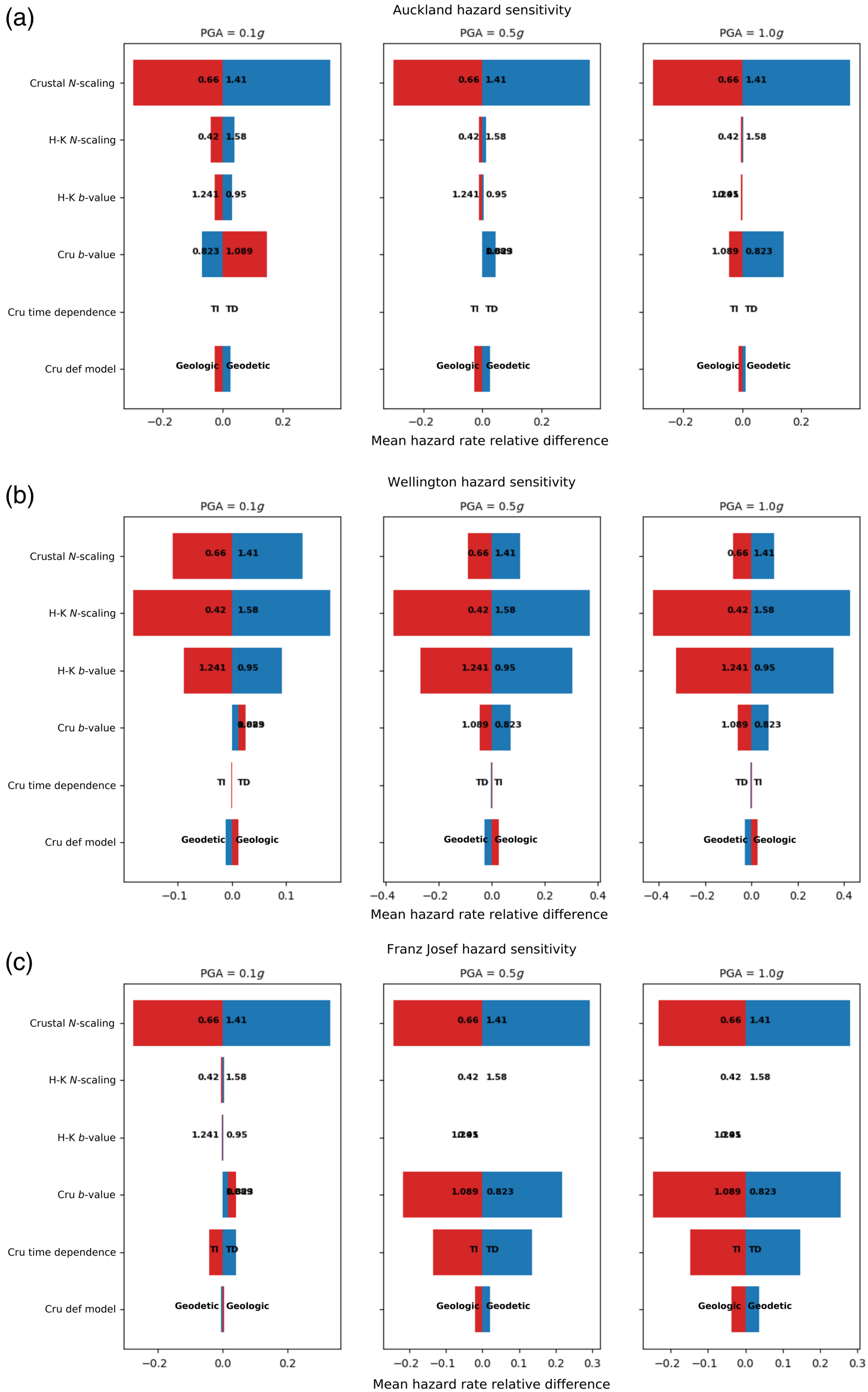

Figure 28. As Figure 27 for single sites. (a) Auckland, (b) Wellington, and (c) Franz Josef. The color version of this figure is available only in the electronic edition.

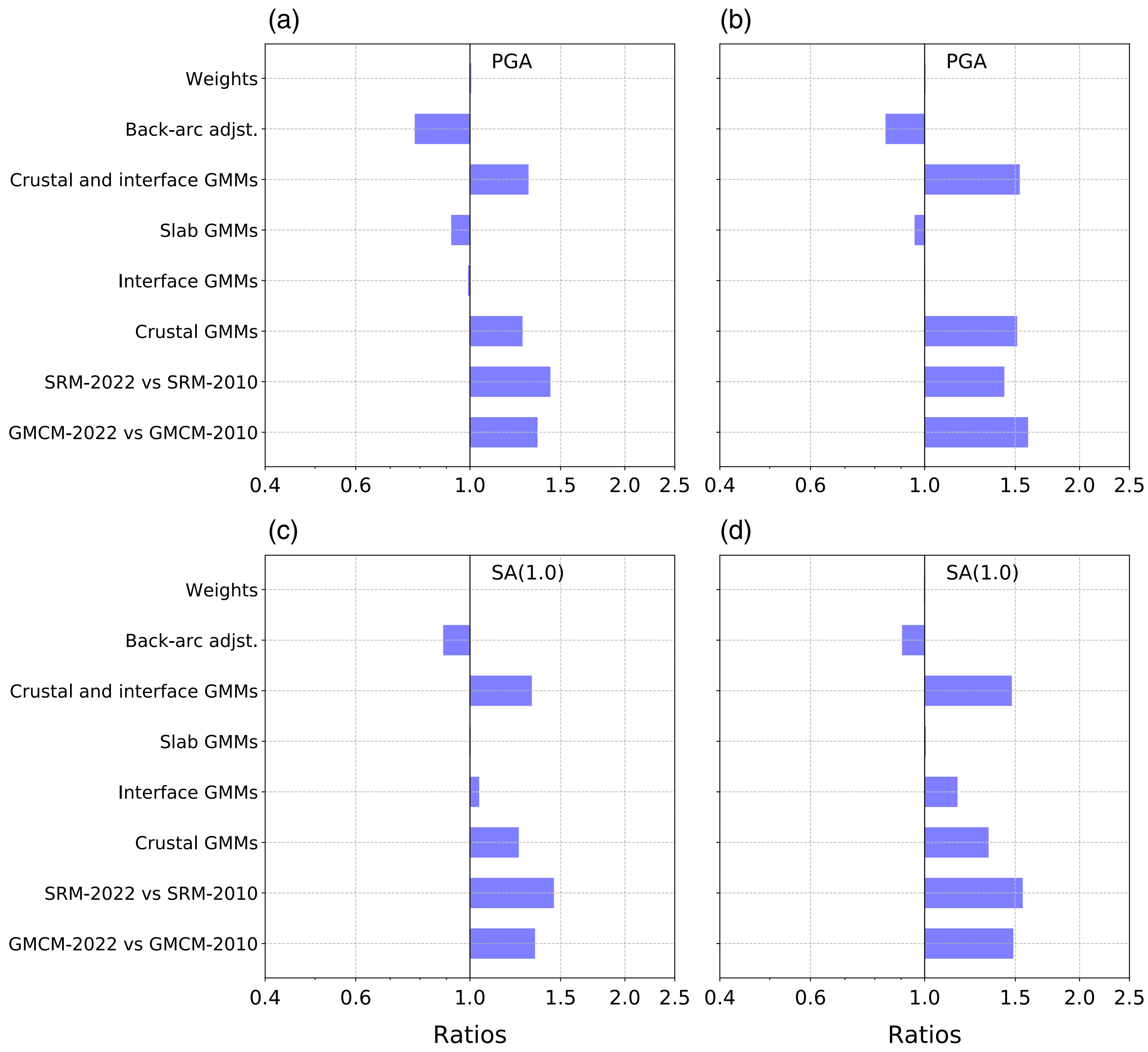

Figure 29. Tornado plot for Auckland. Showing the variability in hazard due to different parameter choices in the logic tree. "Weights" compares the final GMCM logic-tree weights to a uniformly logic tree; "Back-arc adjst" compares with and without the adjustment; "Crustal and Interface GMMs,", "Slab GMMs," "Interface GMMs," and "Crustal GMMs" compare the 2010 and 2022 versions of these components; "GMCM-2022 versus GMCM-2010" compare the total GMCMs from 2022 and 2010 using the 2022 SRM; "SRM-2022 versus SRM-2010" compares the two SRMs using the 2022 GMCM. (a,c) 10% PoE in 50 yr for PGA and SA(1.0), respectively; and (b,d) 2% in 50 yr for PGA and SA(1.0). The color version of this figure is available only in the electronic edition.

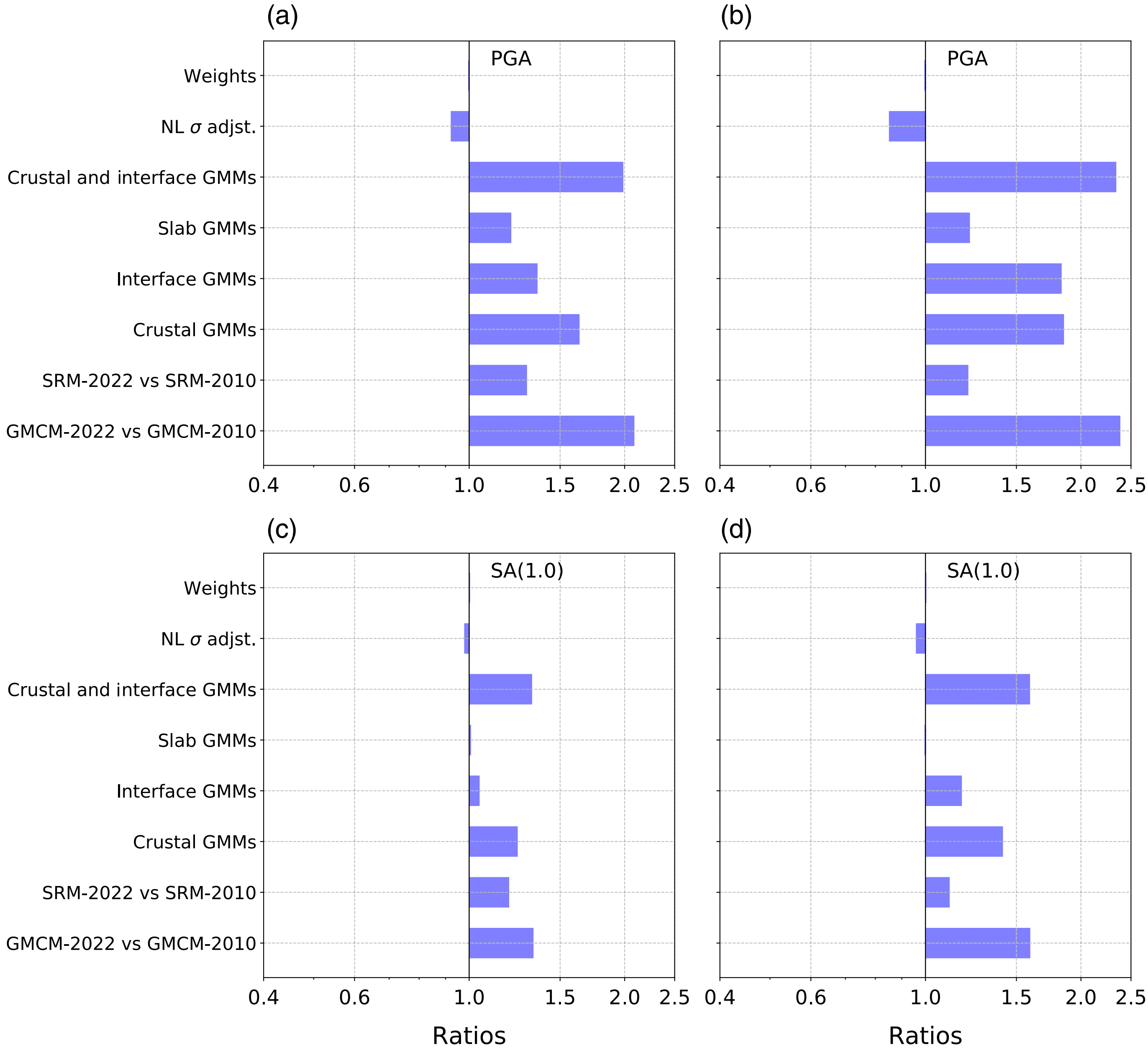

Figure 30. ornado plot for Wellington. Showing the variability in hazard due to different parameter choices in the logic tree. "Weights" compares the final GMCM logic-tree weights to a uniformly logic tree; "Back-arc adjst" compares with and without the adjustment; "Crustal and Interface GMMs," "Slab GMMs," "Interface GMMs," and "Crustal GMMs" compare the 2010 and 2022 versions of these components; "GMCM-2022 versus GMCM-2010" compare the total GMCMs from 2022 and 2010 using the 2022 SRM; "SRM-2022 versus SRM-2010" compares the two SRMs using the 2022 GMCM. (a,c) 10% PoE in 50 yr for PGA and SA(1.0), respectively; (b,d) 2% in 50 yr for PGA and SA(1.0). The color version of this figure is available only in the electronic edition.

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