Hazard Sensitivities Associated with Ground-Motion Characterization Modeling for the New Zealand National Seismic Hazard Model Revision 2022

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ABSTRACT

This article summarizes hazard sensitivities associated with the updated ground-motion characterization modeling (GMCM) scheme adopted in the recent revision of New Zealand National Seismic Hazard Model (NZ NSHM 2022). In terms of impact on ground-motion hazard, the current GMCM scheme (GMCM 2022) results in an overall, at times significant, increase in calculated mean hazard with respect to NZ NSHM 2010. With regard to relative impact, the update in GMCM accounts for the dominant change in high-hazard regions, whereas in low-hazard regions update in source characterization model dominate. Within GMCM 2022, the change in shallow crustal ground-motion models (GMMs) dominates the effect on calculated hazard, whereas change in subduction interface GMMs has a compounding effect for east coast of North Island and southwest of South Island. Impact of the two NZ-specific adjustments to some of the published GMMs is also discussed. The back-arc attenuation adjustment accounts for a 20%–30% reduction in calculated hazard for peak ground acceleration in northwest of North Island, whereas aleatory uncertainty adjustment accounts for 10%–20% reduction in high-hazard regions such as along the east coast of North Island and in the lower west of South Island.

KEY POINTS

- Ground-motion characterization modeling (GMCM) updates dominate changes to hazard in high-hazard regions; in low-hazard regions seismicity rate model (SRM) changes dominate.
- Changes to crustal ground-motion models (GMMs) are most impactful overall; interface GMM changes dominate in high-hazard regions.
- New Zealand (NZ)-specific adjustments to GMMs reduce calculated hazard by 10%–30%.

Supplemental Material

INTRODUCTION

Ground-motion characterization models (GMCM) constitute an essential element of any seismic hazard analysis (Cornell, 1968). Ground-motion models (GMMs) provide a conditional probability distribution of ground motions, given the rupture scenario. The conditional distribution is often described by a lognormal distribution with a median and standard deviation (σ). The σ associated with GMMs is expected to capture the aleatory uncertainty (i.e., inherent randomness) in ground-motion prediction. However, our knowledge about physical phenomena such as earthquake generation, wave propagation, and site effects is limited. Moreover, the data used to constrain such GMMs are not complete. Thus, the uncertainty arising due to our lack of

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knowledge and limited data, which is different from aleatory uncertainty, is termed epistemic uncertainty. Often, epistemic uncertainty in probabilistic seismic hazard analysis (PSHA) studies is captured using multiple GMMs within a probability-based logic-tree framework (Kulkarni *et al.*, 1984). It is also referred to as the "weights on models" approach in the literature. Over the past decade, especially in site-specific hazard studies, a backbone ground-motion modeling framework has been proposed to capture epistemic uncertainty (Bommer, 2013; Atkinson *et al.*, 2014). Constraining epistemic uncertainty is rather challenging in the context of New Zealand owing to the multitude of varied earthquake sources such as, shallow crustal (SC) and subduction (both interface and intraslab) earthquakes contributing to hazard (Stirling *et al.*, 2012; Gerstenberger, Bora, *et al.*, 2022, 2023).

A hybrid GMCM framework was adopted for the 2022 revision of New Zealand National Seismic Hazard Model (NZ NSHM 2022), in which backbone GMMs—two for crustal sources and one for subduction sources—were considered along with the weights on models approach within the GMCM logic tree. Four Next Generation of Attenuation (NGA)-West2 GMMs and three NZ-adjusted GMMs were deemed appropriate after initial evaluation for crustal sources (Bradley *et al.*, 2022, 2024; Lee *et al.*, 2022, 2024). Similarly, three NGA-subduction (Sub) GMMs and one NZ-adjusted backbone GMM were considered for subduction (interface and intraslab) sources. A detailed summary on GMMs and the modeling choices that are adopted for the NZ NSHM 2022 are provided in the accompanying article (Bradley *et al.*, 2024) in the same volume.

This article demonstrates the impact of updates in the GMCM on ground-motion hazard with respect to the GMCM that was adopted in the penultimate version of NZ NSHM 2010 (Stirling *et al.*, 2012). The NZ NSHM 2010 uses a single GMM of McVerry *et al.* (2006) for the GMCM. In addition, we provide a detailed evaluation of hazard changes in terms of relative impacts that are made by updates to the GMMs individually for crustal and subduction sources. In addition, NZ-specific corrections: (1) for back-arc attenuation and (2) nonlinear soil response in σ models were made for several published GMMs (Bradley *et al.*, 2022, 2024). We also show how these two corrections have impacted calculated hazard.

This article is organized as follows: (1) summary of seismic hazard model components examined; (2) brief discussion on the GMCM schemes adopted in NZ NSHM 2010, NZ NSHM 2022 and hence impact on the calculated hazard; (3) relative impact of changes in source characterization models; (4) relative impact on calculated hazard from crustal and subduction GMMs; (5) impact of NZ-specific adjustments; (6) hazard sensitivity to GMCM logic-tree weights; and (7) relative impact of the global GMMs (NGA-West2 and NGA-Sub) versus NZ-specific GMMs on ground-motion hazard.

SUMMARY OF SEISMIC HAZARD COMPONENTS EXAMINED

Seismic source characterization

The hazard sensitivity analysis presented in this article is based on the full seismicity rate model (SRM) from NZ NSHM 2010 and a single (highest weighted) SRM branch from the complete source characterization model of NZ NSHM 2022. The primary reason for selecting a single SRM branch is due to its use in performing sensitivity analysis during the project to triage in which the attention was most warranted. The two SRMs—hereafter referred to as SRM-2010 and SRM-2022—used in the sensitivity analysis are briefly discussed here for completeness. Detailed discussion and comparison of the two source models adopted for this analysis are beyond the scope of this article.

SRM-2010. The NZ NSHM 2010 (Stirling *et al.*, 2012) uses a combination of a fault source model and a distributed seismicity model (DSM). The fault source model uses the dimensions and slip rates of mapped fault sources to develop a single characteristic earthquake in terms of magnitude and frequency for each identified fault source. The fault source model accounts for most of the large events with $\mathbf{M} > 7$ over mapped crustal faults and subduction zones. The DSM adopts a zone-based SRM to account for the observed seismicity across NZ for events $\mathbf{M} > 5$. Rates of such events are constrained using conventional Gutenberg–Richter magnitude–frequency analysis for each zone.

SRM-2022. The SRM-2022 is composed of two main building blocks (Gerstenberger, Van Dissen, *et al.*, 2022, 2023): (1) an inversion fault model (IFM); and (2) a DSM. The IFM uses an inversion-based method to model the occurrence rates for a multitude of potential ruptures on upper-plate faults and subduction interfaces (SIs) that are based on deformation models presented in Van Dissen *et al.* (2023). The DSM complements the IFM based on additional information such as the recent and the historical seismicity observed in NZ. The DSM consists of a hybrid model using multiple datasets and a uniform rate zone model that forecasts rates for low-seismicity regions. To capture epistemic uncertainty, the SRM-2022 involves: thirty six logic-tree branches for crustal sources, nine logic-tree branches for SI sources, and one single branch to model the subduction intraslab (SS) sources. Reader is referred to Gerstenberger, Van Dissen, *et al.* (2022, 2023) for further details on SRM-2022. We used a single highest weighted branch of the SRM-2022 to demonstrate the impact of two NZ-specific modeling choices, that is, correction for back-arc attenuation and correction in σ for nonlinear soil response of some of the GMMs considered for NZ NSHM 2022.

Ground-motion characterization models

The two GMCMs adopted in NZ NSHM 2010 and NZ NSHM 2022, hereafter referred to as GMCM-2010 and GMCM-2022, respectively, are briefly discussed in the following subsections.

GMCM-2010. The NZ NSHM 2010 (Stirling *et al.*, 2012) uses GMMs developed by McVerry *et al.* (2006), hereafter McV06, for peak ground acceleration (PGA) and 5% damped acceleration response spectra. Importantly, the GMCM-2010 uses only one GMM for the ground-motion characterization for each tectonic type. The McV06 model was calibrated on a dataset compiled across NZ up to the end of 1995. Moreover, the McV06 GMM prescribes model parameters (or coefficients) for crustal, SI, and SS separately. Site effects are modeled in terms of NZ-specific site subsoil classes (McVerry *et al.*, 2006), and results are derived for the larger of the two horizontal components. Separate model coefficients were provided for Taupō volcanic zone.

It is worth mentioning here that the McV06 GMM, adopted in GMCM-2010, is calibrated on the larger of the two horizontal components, whereas the GMMs used in GMCM-2022 are calibrated on RotD50 orientation. Thus, for comparisons shown here, the correction proposed by Bradley and Baker (2015) was applied to the median model of McV06 to convert to equivalent RotD50 values.

GMCM-2022. The NZ NSHM 2022 adopts a hybrid modeling approach to capture the plausible range of epistemic uncertainty that combines weights on the models approach with backbone modeling framework. Lee *et al.* (2024) have performed detailed testing for a set of candidate GMMs that were considered appropriate in NZ. More details on the GMMs, applicability, and parameter choices are summarized in another article in the same volume (Bradley *et al.*, 2024). The sensitivity analysis presented here pertains to the GMMs adopted in the final NZ NSHM 2022 GMCM logic tree. For crustal sources, a total of seven GMMs were considered that comprise four global GMMs (Abrahamson *et al.*, 2014; Boore *et al.*, 2014; Campbell and Bozorgnia, 2014; Chiou and Youngs, 2014) from NGA-West2 along with three GMMs (Bradley, 2013; Atkinson, 2022; Stafford, 2022) adjusted to NZ-specific magnitude and distance scaling. The two recent GMMs of Atkinson (2022) and Stafford (2022) are developed under the backbone ground-motion modeling framework with their inherent upper and lower branches to capture epistemic uncertainty. Hereafter, Abrahamson *et al.* (2014), Boore *et al.* (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014) will be referred to as ASK14, BSSA14, CB14, and CY14, respectively. Similarly, the Bradley (2013), Atkinson (2022), and the Stafford (2022) GMMs will be referred as B13, A22, and S22, respectively.

The NZ NSHM 2022 GMCM used three recently derived NGA-Sub models for subduction sources (both interface and intraslab): Abrahamson and Gülerce (2020), Kuehn *et al.* (2020), and Parker *et al.* (2022), hereafter referred as AG20, KBCG20, and PSBAH22, respectively. In addition, subduction sources were modeled by A22. It is worth mentioning that AG20 and KBCG20 have developed NZ-specific regional models for subduction events, which were not considered appropriate for hazard analysis after initial evaluation of the GMMs (Bradley *et al.*, 2022; Lee *et al.*, 2022). The main reason for not including the NZ-specific regional models of AG20 and KBCG20 in the GMCM logic tree was that such regional adjustments (in these models) were not considered robust mainly on two grounds: (1) such adjustments were derived on earlier version of the NZ strong-motion database (Van Houtte *et al.*, 2017); and (2) uncertainties in predictor variables such as in-basin depth parameter were not well constrained. Thus, in this article and for NZ NSHM 2022 (Gerstenberger, Bora, *et al.*, 2022, 2023), the global versions of these models are used. For more details regarding applicability, predictor variables range, the additional NZ-specific adjustments (in the published GMMs) reader is referred to the accompanying article Bradley *et al.* (2024) in the same volume. Bradley *et al.* (2024) provide detailed comparisons of median and aleatory uncertainty (σ) of the GMMs for different dominant scenarios. However, for completeness, comparisons of full median response spectra and σ are presented in the supplemental material available to this article for various dominant rupture scenarios in NZ.

For detailed discussion on the final GMCM logic tree for SC, SI, and SS, reader is referred to the overview article (in the same volume) of Gerstenberger, Bora, *et al.* (2022, 2023). However, for completeness, the logic trees are shown in the supplemental material. The branch weights shown are based on expert elicitation that were used for final hazard computation (Gerstenberger, Bora, *et al.*, 2023).

Treatment of site effects

All the GMMs considered in the NZ NSHM 2022 GMCM parameterize site effects using the time-averaged shear-wave velocity in the upper 30 m of the soil column (V_{S30}). All the crustal GMMs, except A22, prescribe an additional site-term based on basin depth parameters ($Z_1/Z_{2.5}$) to account for basin response. However, in the absence of reliable site-specific Z_1 (depth to 1 km shear-wave velocity horizon) and $Z_{2.5}$ (depth to 2.5 km/s shear-wave velocity horizon) data (Wotherspoon *et al.*, 2022, 2024), we adopt the generic $V_{S30} - Z_1$ and $V_{S30} - Z_{2.5}$ correlations calibrated on California data from Chiou and Youngs (2014) and Campbell and Bozorgnia (2014), respectively. For subduction GMMs, none of the models prescribe separate basin depth-scaling terms for their global versions. Hence, for the hazard sensitivity analysis presented in this article, the site condition in terms of V_{S30} is fixed to 250 m/s as representative of the dominant site condition across major urban centers in NZ. The GMM used in NZ NSHM 2010 utilizes a NZ-specific site subsoil class approach to account for the site effects Standards New Zealand (2004). Thus, an equivalent site subsoil class D is considered the most appropriate for comparisons shown in this article and provides a baseline comparison for national hazard. However, it is worth mentioning that there is no one-to-one correspondence between NZ site subsoil class and V_{S30}. Kaiser et al. (2022, 2024) discuss this aspect and also demonstrate that it can lead to considerable variability in site-specific hazard changes within a given urban area.

HAZARD SENSITIVITY EXAMINATION

This article mainly evaluates hazard sensitivity in the GMCM scheme between NZ NSHM 2010 and NZ NSHM 2022, investigating the impact for each tectonic type and NZ-specific first-order adjustments to the published GMMs. However, such sensitivities are always contingent on the SRM used for hazard calculations. Thus, we also show the effect on hazard when the SRM-2010 is replaced by a single branch from SRM-2022. This helps us to evaluate how the sensitivities presented here are affected by the change in SRM and also their relative effect in comparison with the changes (in hazard) caused by GMCM changes.

The hazard sensitivity is presented in two ways: (1) graphical comparison of full hazard curves at selected locations and for selected oscillator periods; and (2) linear ratio maps of intensity measures (IMs) (corresponding to a selected annual probability of exceedance [APoE]) over the entire country on a $0.2° \times 0.2°$ grid. The ratios are computed at each grid point for the selected IMs corresponding to 10% and 2% probability of exceedance (PoE) in 50 yr. The hazard sensitivities are presented for two IMs: PGA and spectral acceleration (SA) at oscillator (or vibration) period T = 1.0 s, hereafter SA (1 s). The changes in hazard on a national scale are shown in terms of ratio maps for PGA and SA (1 s).

The hazard sensitivity analysis is specifically examined for following model components:

- impact of the GMCM-2022 logic tree as a whole on calculated hazard with respect to the GMCM-2010;
- effect of SRM-2022 vs. SRM-2010 on such hazard sensitivities and their relative impact in relation to GMCM changes;
- impact of GMCM-2022 GMMs separately for each tectonic type such as crustal, interface, and intraslab GMMs with respect to the GMMs used in GMCM-2010;
- impact of NZ-specific first-order adjustments to the published GMMs: (1) back-arc attenuation adjustment on hazard; (2) adjustment in σ for nonlinear site effects on hazard using SRM-2022;
- impact of uniform versus nonuniform GMCM logic-tree weights on calculated hazard using SRM-2022; and
- impact of global GMMs versus NZ-specific GMMs.

Effect of using GMCM-2022 versus GMCM-2010

First, we show an impact on calculated hazard when the GMCM-2010 is replaced by the GMCM-2022, keeping the source model (SRM-2010) identical for the two combinations of hazard calculations. We computed hazard at 35 major locations across NZ; however, hazard curves in Figure 1 are presented for major urban centers in North and South Islands due to space constraints: Auckland, Wellington, Christchurch, and Te Anau. The PGA hazard map for 10% PoE in 50 yr from the final hazard results (Gerstenberger, Bora, et al., 2022, 2023) along with mapped faults (Gerstenberger, Bora, et al., 2023) in Figure 1 is used as a reference to provide context for various hazard sensitivities presented in this study. Thus, the choice of these locations (towns) is motivated by the dominant tectonics as well as the hazard zone (lower or higher) they fall in. Additional hazard curves for Hamilton, New Plymouth, Napier, and Dunedin are presented in the supplemental material. Hazard computation with GMCM-2022 results in 3024 realizations of hazard curves. Thus, in Figure 1, in addition to mean hazard, the 10th and 90th percentiles are also shown. For NZ NSHM 2010, only a single estimate of hazard is obtained owing to the use of a single source model and a single GMM. At all locations, the (mean) calculated hazard is observed to be similar toward the higher APoEs, whereas the curves diverge toward lower APoEs. Notably, in high-hazard areas, such as Wellington and Te Anau, the hazard changes at 10% PoE in 50 yr and 2% PoE in 50 yr are relatively larger in comparison with that for Auckland and Christchurch. The NZ NSHM 2010 hazard, for 10% PoE and 2% PoE in 50 yr, is close to or below the 10th percentile bounds from NZ NSHM 2022, whereas it is within the uncertainty bounds for Auckland and Christchurch.

Figure 2 depicts the ratio maps for the two combinations of hazard calculations. For the ratios, ground-motion IM levels corresponding to 10% and 2% PoE in 50 yr are chosen. Thus, the ratios are computed as $\mathrm{IM}_{\mathrm{GMCM-2022}}/\mathrm{IM}_{\mathrm{GMCM-2010}}$, keeping the SRM-2010 common for the two hazard runs. Clearly, the mean hazard increases over the entire country with the update in the GMCM-2022. The highest increase is along the eastern part of the North Island, whereas the lowest increase is seen in Northland and toward the southeastern portion (e.g., Dunedin) of the South Island. It can also be observed that the changes for PGA are larger than that for SA (1 s). The relative changes in calculated hazard shown here account for the two NZ-specific corrections discussed in the Effect of NZ-specific GMM adjustments section.

Effect of using SRM-2022 versus SRM-2010

We show the impact of changes in SRM (SRM-2022 versus SRM-2010) on the hazard sensitivities presented in this article by showing the comparison of hazard curves and hazard ratio maps with the two SRMs. Figure 3 shows comparison of hazard curves at the same four locations in Auckland, Wellington, Christchurch, and Te Anau with two different SRMs, that is, SRM-2010 and SRM-2022 while keeping GMCM-2022 common. We used the highest weighted (single) branch of the SRM-2022 for these computations. In Figure 3, hazard curves from the NZ NSHM 2010 are also shown to evaluate

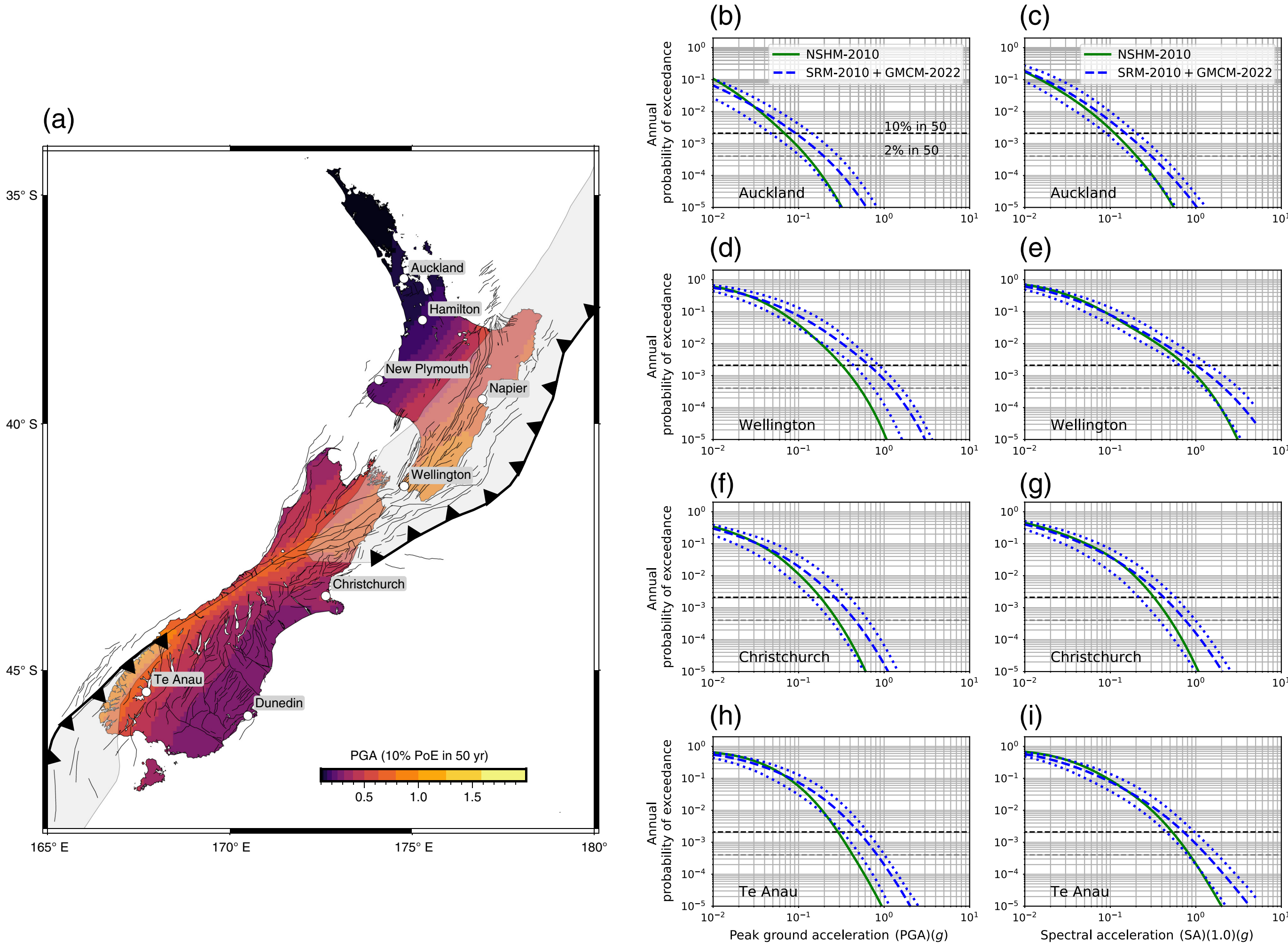


Figure 1. (a) Peak ground acceleration (PGA) hazard map for 10% probability of exceedance (PoE) in 50 yr from New Zealand National Seismic Hazard Model (NZ NSHM) 2022 (Gerstenberger, Bora, *et al.*, 2023) along with the locations of major towns considered for hazard sensitivity analysis in this article. The gray shaded regions show two subduction zones Hikurangi–Kermadec (proximal to northeast of North Island) and Puysegar (proximal to southwest of South Island). (b,d,f,h) Hazard curves comparisons from ground-motion characterization modeling (GMCM)-2010 and GMCM-2022 keeping seismicity rate model (SRM)-2010 common for peak ground acceleration (PGA) at a site in Auckland, Wellington, Christchurch, and Te Anau, respectively. (c,e,g,i) Hazard curves comparisons for spectral acceleration, SA (1 s) at the same locations, respectively. The dotted curves in each panel (b)–(i) indicate the 10th and 90th percentile hazard curves in addition to mean (dashed) from GMCM-2022. The hazard map and hazard curves are shown for $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

the relative effect of SRM changes in relation to GMCM changes presented in Figure 1. In high-hazard areas, such as Wellington and Te Anau, the change in SRM results in relatively lower increase in hazard in comparison with that at Auckland and Christchurch. In fact, in Te Anau, the hazard for 10% PoE in 50 yr is similar for the two SRMs used in this study. The change in SRM is a major driver of the increase in hazard in low-hazard areas such as Auckland and Christchurch. Figure 4 shows the ratio maps for PGA and SA (1 s) corresponding to 10% PoE and 2% PoE in 50 yr. The ratios are computed as $\mathrm{IM}_{\mathrm{SRM-2022}}/\mathrm{IM}_{\mathrm{SRM-2010}}$, keeping the GMCM-2022 common. Clearly, relatively larger ratios are observed in the northwestern part of the North Island and in southeastern part of the South Island. The change in SRM-2022 also results in a decrease in hazard in small regions around the central South Island, which can be due to various reasons, such as changes in the rates associated with major faults as well as changes in the DSM. However, further investigation of such issues is beyond the scope of this article. Reader is referred to Gerstenberger, Bora, *et al.* (2023) for a more detailed investigation of SRM sensitivities.

Overall, the analysis presented in this subsection illustrates that for high-hazard regions, along the east coast of North Island and lower southwest of the South Island, the hazard changes are dominated by the change in GMCM. Clearly, reflecting the impact of the two subduction zones (as also discussed subsequently)—Hikurangi-Kermadec and Puysegar, respectively. At the same time, in low-hazard regions, such as upper north of the North Island and lowereast of the South Island, the change in SRM dominates the change in hazard.

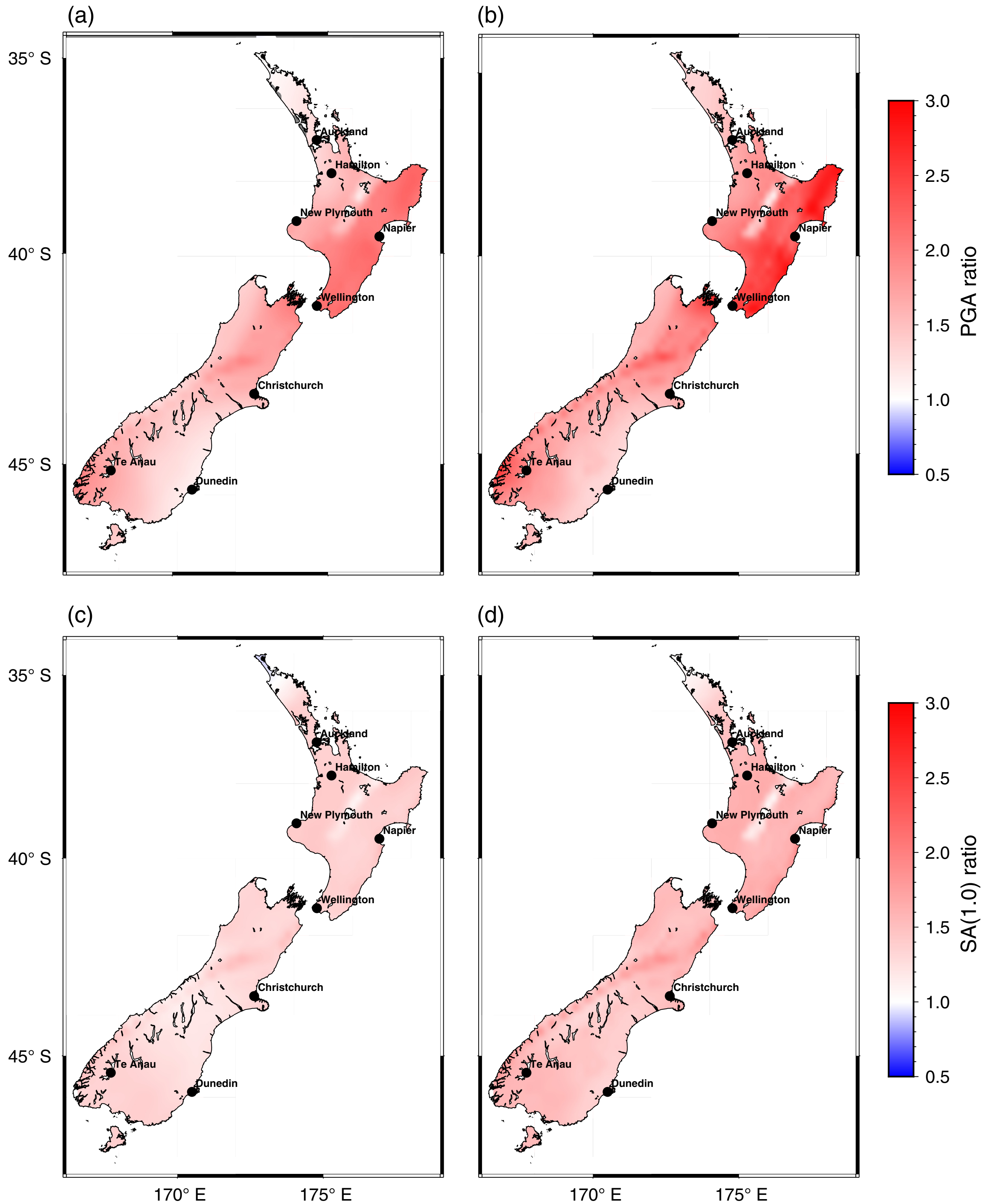
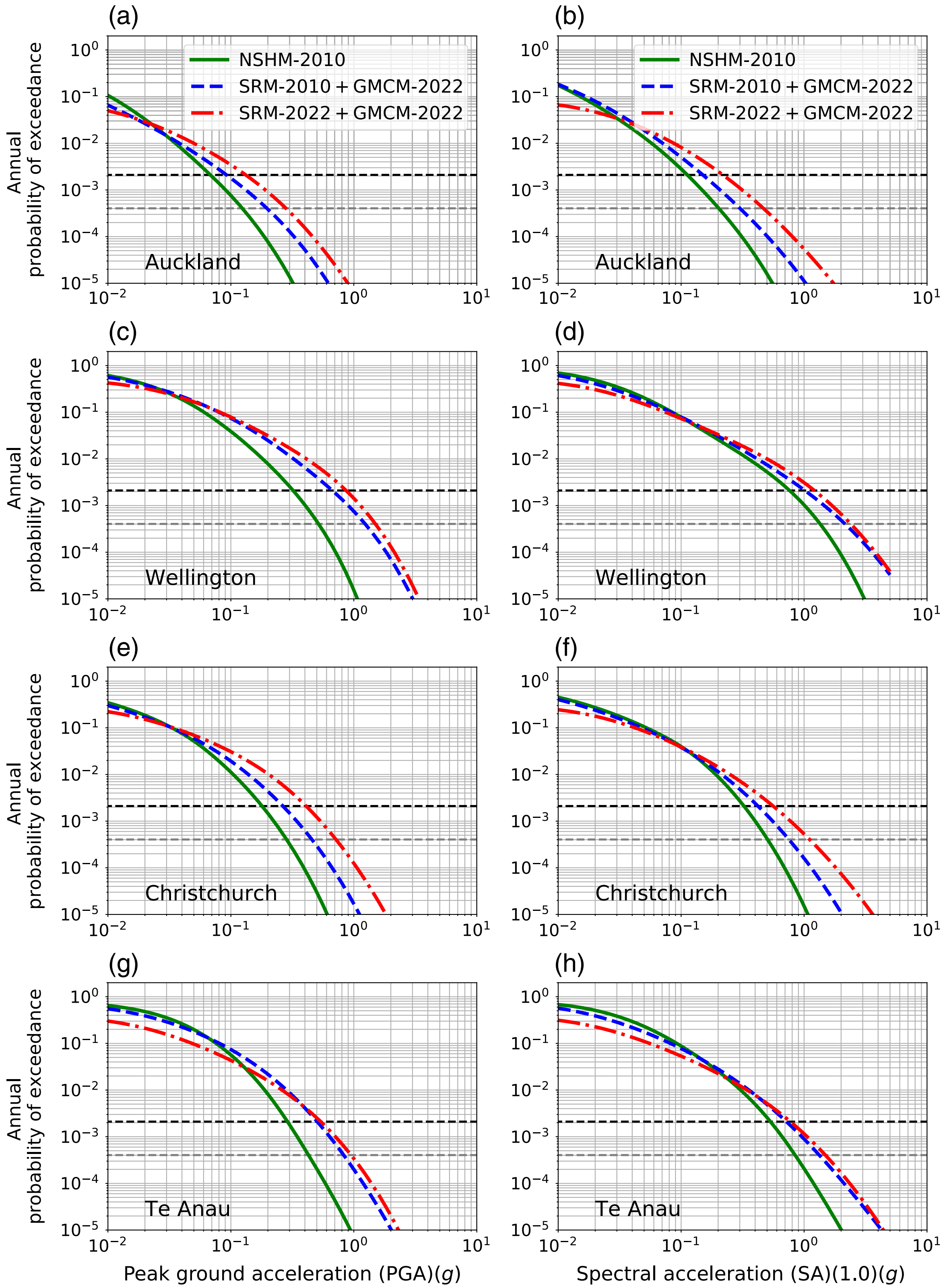


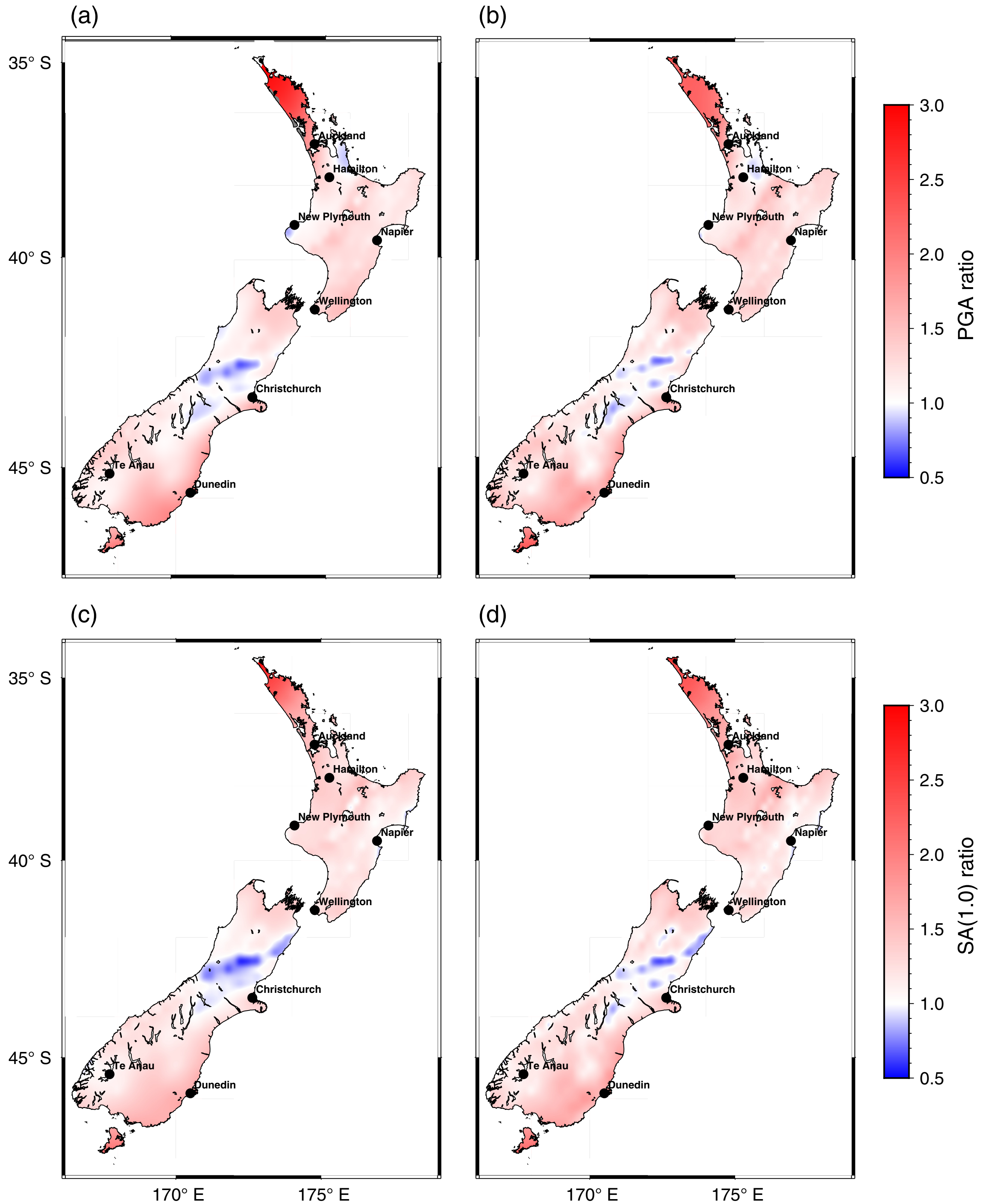
Figure 2. Hazard ratio maps for PGA and SA (1 s). The ratio is defined as GMCM-2022/GMCM-2010 keeping SRM-2010 common for $V_{S30} = 250$ m/s. (a,c) The ratios for 10% probability of exceedance (PoE) in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

This clearly highlights the role of the dominant tectonics in the respective regions. The relative contributions of the three tectonic types (using a highest weighted SRM-2022 branch) in hazard at four major locations: Auckland, Wellington, Christchurch, and Te Anau are shown in Figure 5. The same



plots for Hamilton, Napier, New Plymouth, and Dunedin are shown in the supplemental material. From these plots, it is clear that the SI sources dominate hazard along the eastern coast of North Island (Wellington, Napier) and in the southwestern part of the South Island (Te Anau). In low-hazard regions, such as Auckland, New Plymouth, Christchurch, and Dunedin, the

Figure 3. Comparisons of hazard curves between hazard from SRM-2010 and hazard SRM-2022 keeping GMCM-2022 common. (a,c,e, g) Comparisons for PGA at a site in Auckland, Wellington, Christchurch, and Te Anau, respectively. (b,d,f,h) Comparisons for SA (1 s) at the same locations, respectively. The curves are shown for $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.



dominant contribution comes from SC sources. Having this information of dominant source types across various regions of NZ, we further dissect these hazard changes due to GMCM change (GMCM-2022) into the effects of GMM updates for individual tectonic type, which is examined in the next subsection.

Figure 4. Hazard ratio maps for PGA and SA (1 s). The ratio is defined as SRM-2022/SRM-2010 keeping GMCM-2022 common, for $V_{S30} = 250$ m/s. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

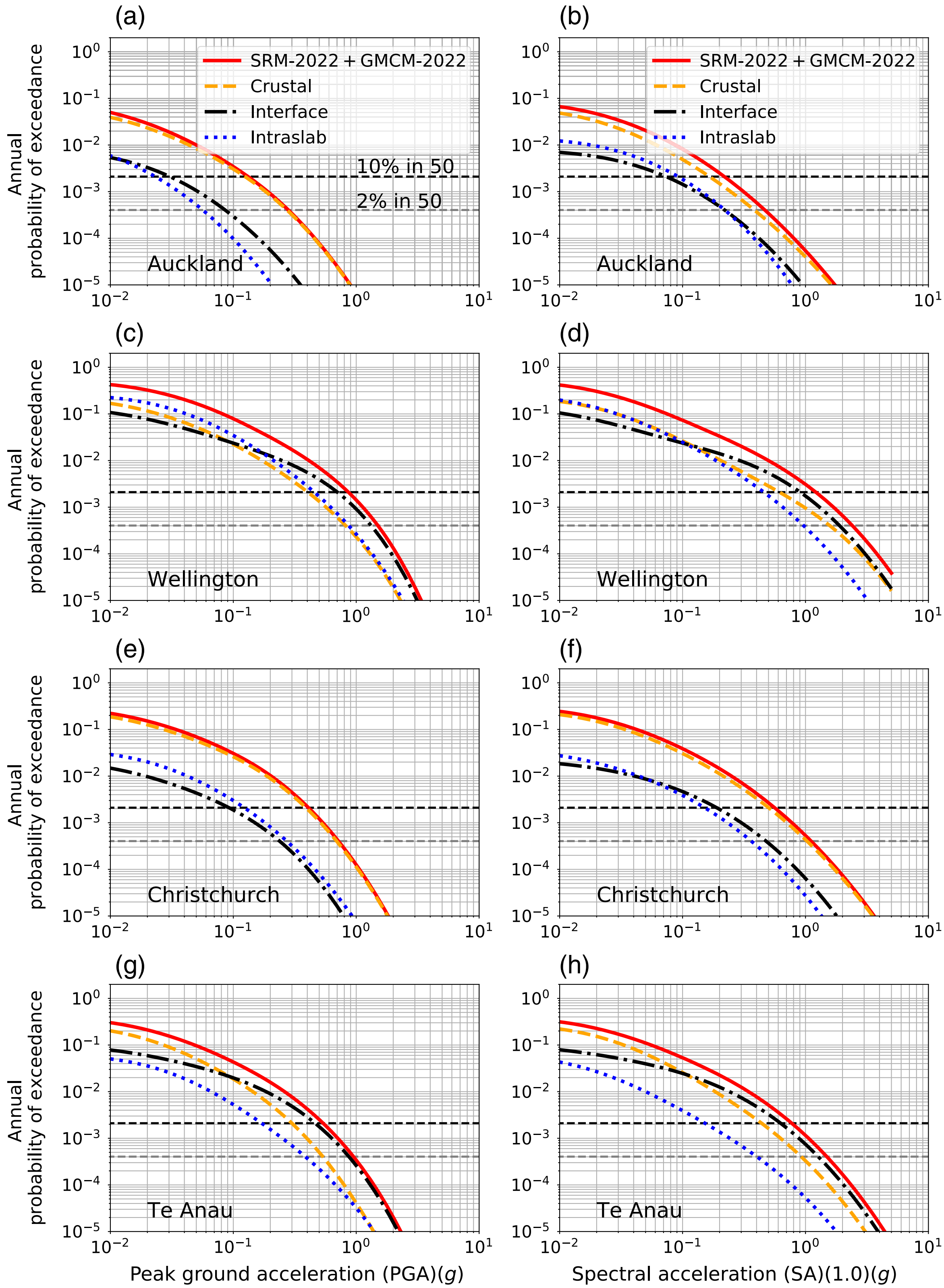


Figure 5. Hazard curves showing relative contribution of the three source types at Auckland, Wellington, Christchurch, and Te Anau. (a,c,e,g) Hazard curves for PGA. (b,d,f,h) Hazard curves for SA (1 s). The hazard curves are shown using SRM-2022 and GMCM-2022 for $V_{S30} = 250$ m/s. The color version of this figure is available only in the electronic edition.

Effect of changing GMMs for individual tectonic types

We further dissect the change in hazard (due to full GMCM-2022) into contributions that are coming from GMMs related to different tectonic types, that is, SC, SI, and SS. For that purpose, hazard calculations were performed in four different permutations: (1) update only SC GMMs while keeping SI and SS GMMs identical to GMCM-2010; (2) update only SI GMMs while keeping SC and SS GMMs identical to GMCM-2010; (3) update only SS GMMs while keeping SC and SI GMMs identical to GMCM-2010; and (4) update SC and SI GMMs while keeping SS GMMs identical to GMCM-2010. The SRM-2010 was kept common in these four hazard iterations. Figures 6–9 depict full hazard curves at Auckland, Wellington, Christchurch, and Te Anau corresponding to GMM permutations (1), (2), (3) and (4), respectively. Furthermore, hazard ratio maps are also plotted for all four permutations of GMMs but due to space constraints are presented only for (1) and (2) in Figures 10 and 11, respectively. For the permutations (3) and (4), the ratio maps are provided in the supplemental material. In each case, the ratios are computed with respect to full NZ NSHM 2010. That means, the hazard results from NZ NSHM 2010 are used as denominators in computing ratios for the four cases. For Auckland and Christchurch, the major increase in hazard (due to changes in GMCM) is mainly driven by the updated SC GMMs (Fig. 6). Clearly, the updated SC GMMs used in the NZ NSHM 2022 are responsible for a nationwide increase in hazard with respect to NZ NSHM 2010 for both PGA and SA (1 s; Fig. 10). In Wellington and Te Anau, the baseline increase in hazard is provided by the change in SC GMMs compounded by the effect of change in SI GMMs (Fig. 7). In terms of spatial variation, the SI GMMs contribute to the increase in hazard mainly, as expected, around eastern part of the North Island proximal to the Hikurangi–Kermadec subduction zone and southwestern portion of the South Island close to Puysegur subduction zone (Fig. 11). Moreover, the relative increase due to updated SI GMMs is larger for smaller APoEs that essentially reflects the occurrence rates associated with such scenarios in the SRM-2010. The impact of updated SS GMMs is rather small in comparison with the impact of updated SC and SI GMMs. Particularly, the difference is found to be practically negligible for SA (1 s) (Fig. 8). On the national scale, the impact of updated SS GMMs is mostly limited to North Island where they account for a small reduction in hazard for PGA in the northwestern portion. This reduction can be partially attributed to the back-arc attenuation adjustment discussed later in the Effect of NZ-specific GMM adjustments section. Difference in distance scaling of updated SS GMMs and McV06 can also cause such a reduction in hazard. Overall, the major change (increase) in hazard for both PGA and SA (1 s) is mainly attributed to the updated SC and SI GMMs in the GMCM-2022 logic tree (Fig. 9).

Effect of NZ-specific GMM adjustments

As mentioned earlier, and discussed in detail in the accompanying article Bradley *et al.* (2024) in the same volume, two major NZ-specific GMM corrections were performed: (1) stronger attenuation in the back-arc region; and (2) lower aleatory uncertainty (σ) accounting for nonlinear soil response. Hence, in the following two subsections, we evaluate the impact of these two NZ-specific corrections on the hazard estimates. For the hazard sensitivities presented in the last two sections, the adjusted GMMs are used as they were used in the final hazard calculations (Gerstenberger *et al.*, 2022, 2023).

Back-arc attenuation adjustment. The back-arc attenuation adjustments were made only on (median) GMMs of A22, AG20, KBCG20, and PSBAH22 using the BC Hydro GMM (Abrahamson *et al.*, 2016) prescribed adjustments (Bradley *et al.*, 2024). Figure 12 shows comparison of hazard curves at three locations in the back-arc region (the northwestern portion of the North Island, shown in Fig. 13): Auckland, Hamilton, and New Plymouth using the highest weighted branch from the SRM-2022 as the source characterization model. Given the impact of updated SRM-2022 on hazard in low-hazard areas such as Auckland, we chose to show these hazard sensitivities with the updated SRM-2022. Moreover, our decision to include such adjustments was motivated by observing the hazard sensitivities with the updated SRM-2022. As expected, the major impact of back-arc corrections is observed for PGA, whereas it is very small for SA (1 s). Importantly, the impact is observed to be similar for all APoEs. Hamilton is the most affected location by such adjustments.

Furthermore, the ratio maps are also shown for IMs corresponding to PoE 10% in 50 yr and 2% in 50 yr. The ratios are computed, at each grid point, as $IM_{\text{back-arc-adjst.}}/IM_{\text{without-back-arc-adjst.}}$ in the intraslab GMMs. Thus, the ratios directly express the relative reduction in hazard due to the back-arc attenuation adjustments. Figure 13 shows such a ratio map with the highest weighted SRM-2022 branch as the source characterization model. The polygon outlined in black at top of each map shows the region considered as the back-arc region (Bradley *et al.*, 2024). A rather important observation that can be made from Figure 13 is that the impact of back-arc adjustments is not significant north of Auckland in the Northland region. This again exhibits the impact of dominant sources in the region that can be attributed mostly to updated DSM (see Figs. 1 and 4). Hazard curves for the same locations, that is, Auckland, Hamilton, and New Plymouth and hazard ratio maps considering SRM-2010 as the source characterization model, are provided in the supplemental material.

Nonlinear soil response adjustment in aleatory uncertainty. In this subsection, we demonstrate the impact of nonlinear soil response adjustment made in σ models of KBCG20, PSBAH22, and A22 GMMs. Usually, the σ associated with GMMs exhibits a heteroscedastic behavior with dependence on predictor variables such as magnitude and distance. This usually gets reflected in reduced σ values for larger rupture scenarios toward softer soil sites, for example, the σ models of AG20 and CY14. As elaborated upon in Bradley *et al.*

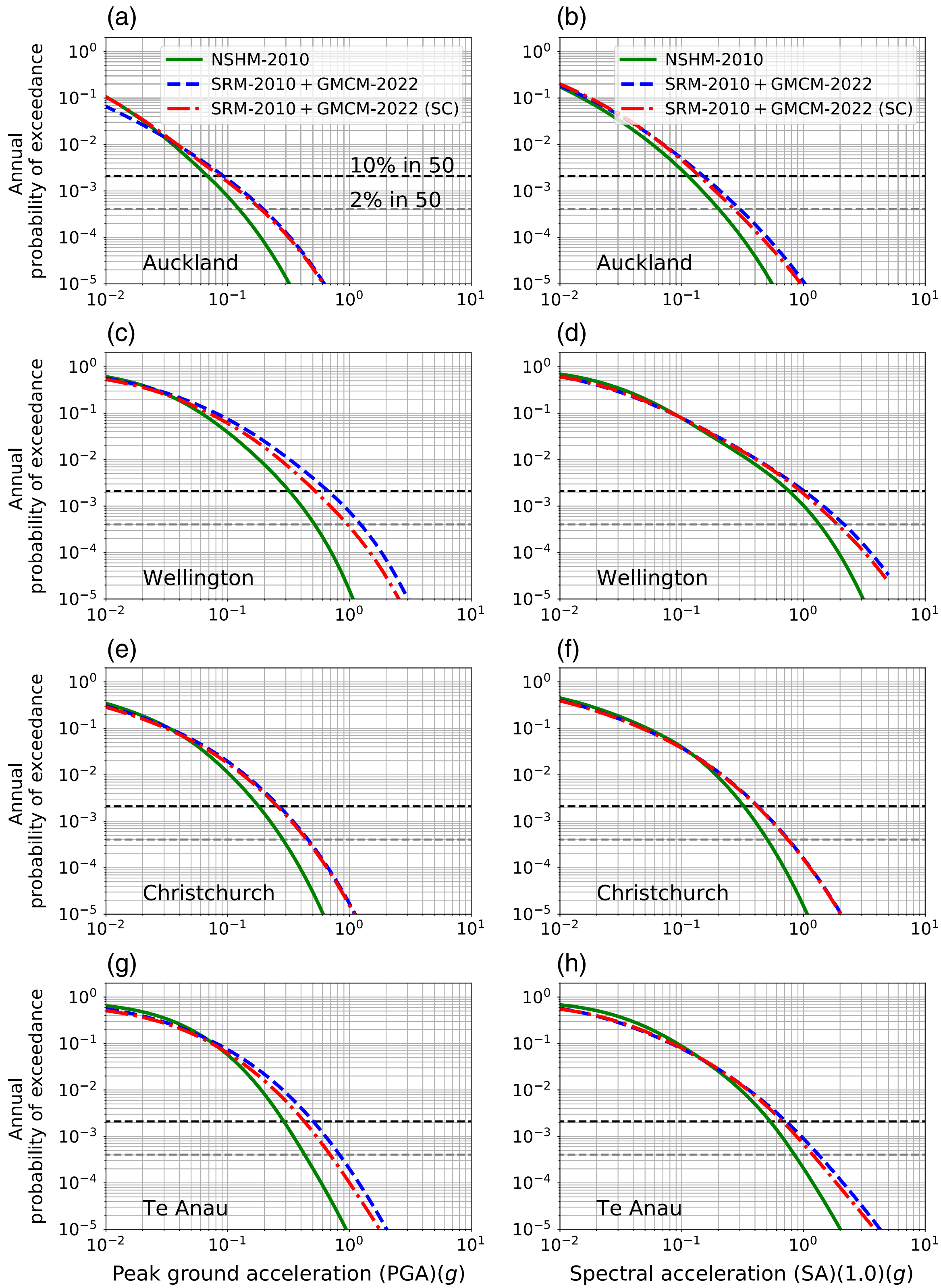


Figure 6. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau for $V_{S30} = 250$ m/s. (a,c,e,g) Comparisons for PGA. (b,d,f, h) Comparisons for SA (1 s). Here SRM-2010 stands for seismicity rate model in NZ NSHM 2010, and GMCM-22 (full) stands for ground-motion model characterization modeling 2022 with full logic trees for all shallow crustal (SC), subduction interface (SI), and subduction intraslab (SS) sources. GMCM-2022 (SC) means the GMCM logic tree with only SC ground-motion models (GMMs) updated with other GMMs identical to GMCM-2010. The color version of this figure is available only in the electronic edition.

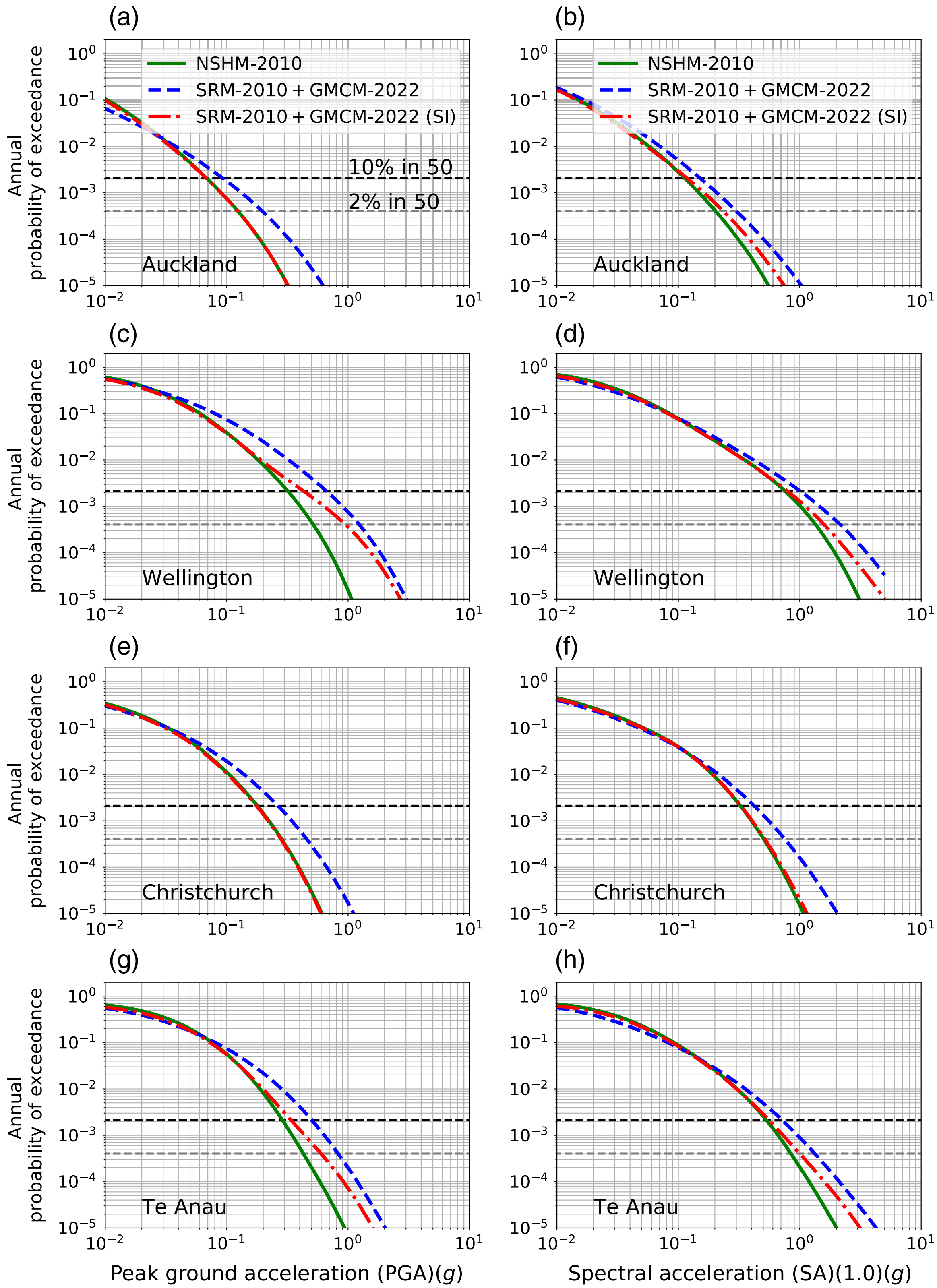


Figure 7. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau for $V_{S30} = 250$ m/s. (a,c,e,g) Comparisons for PGA. (b,d,f,h) Comparisons for SA (1 s). Here SRM-2010 stands for seismicity rate model in NZ NSHM 2010, and GMCM-22 (full) stands for ground-motion model characterization modeling 2022 with full logic trees for all SC, SI, and SS sources. GMCM-22 (SI) means the GMCM logic tree updated only for SI GMMs with other GMMs identical to GMCM-2010. The color version of this figure is available only in the electronic edition.

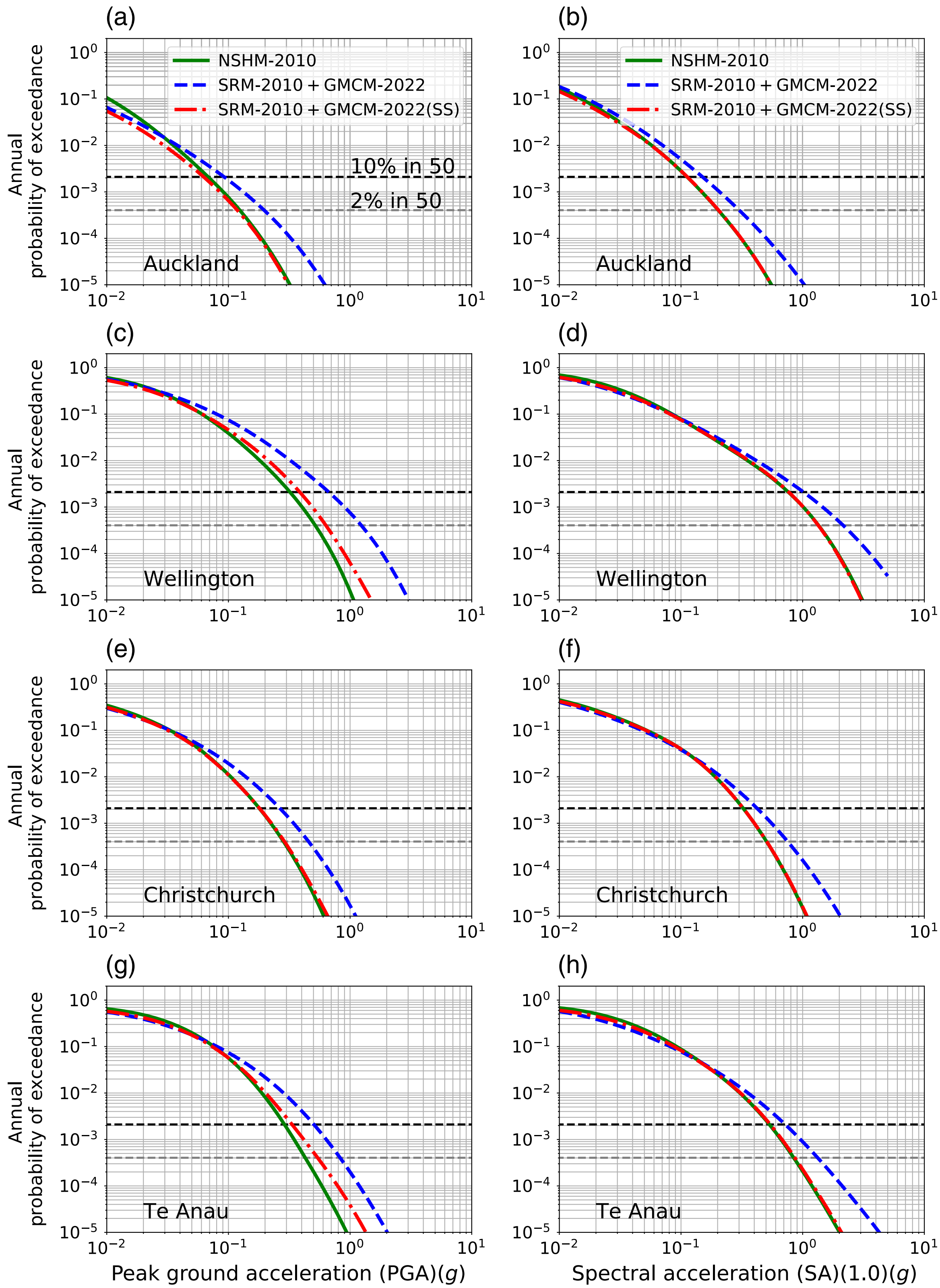


Figure 8. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau for $V_{S30} = 250$ m/s. (a,c,e,g) Comparisons for PGA. (b,d,f, h) Comparisons for SA (1 s). Here SRM-2010 stands for seismicity rate model in NZ NSHM 2010, and GMCM-22 (full) stands for ground-motion model characterization modeling 2022 with full logic trees for all SC, SI, and SS sources. GMCM-22 (SS) means the GMCM logic tree updated only for SS GMMs with other GMMs identical to GMCM-2010. The color version of this figure is available only in the electronic edition.

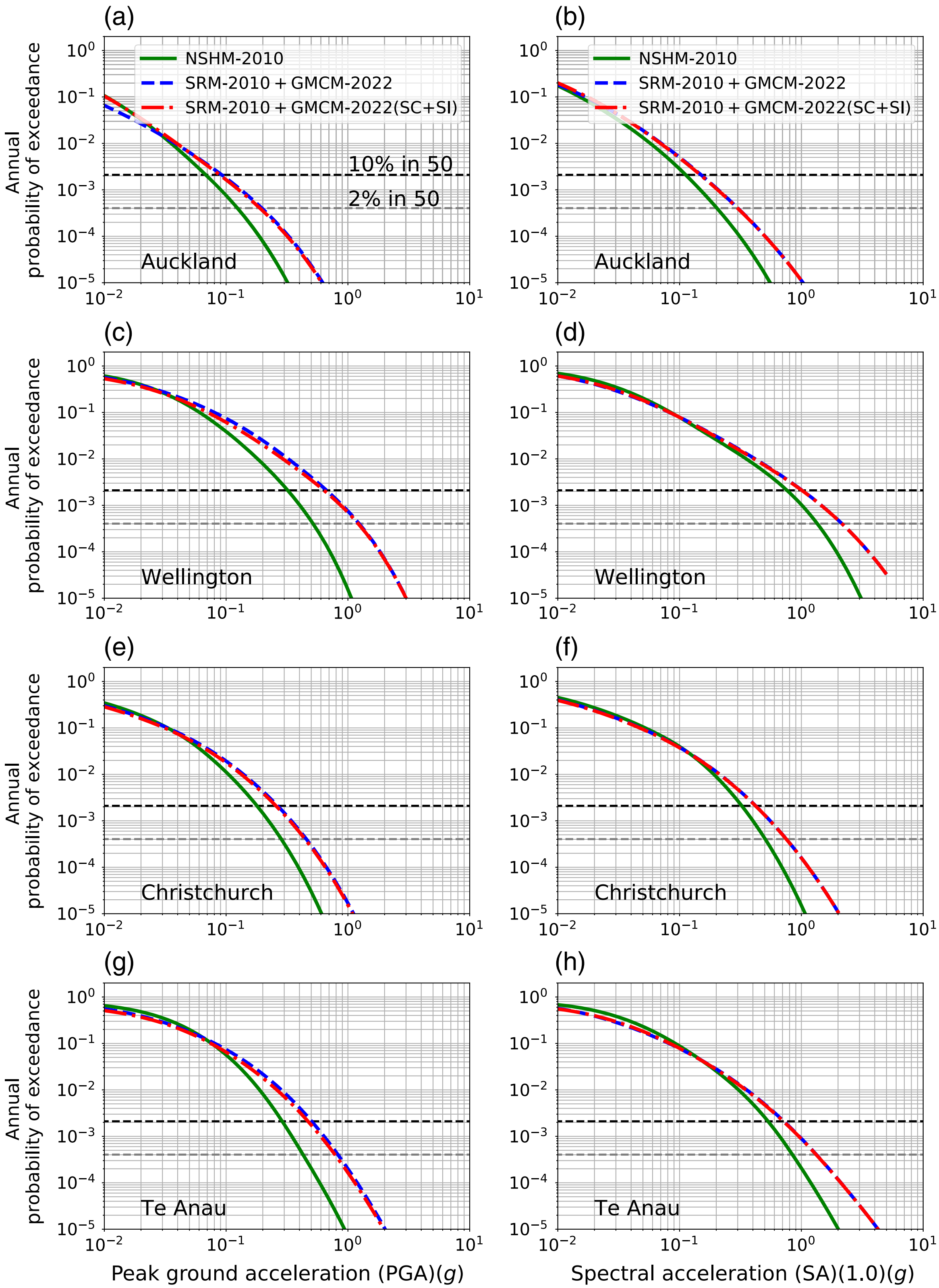
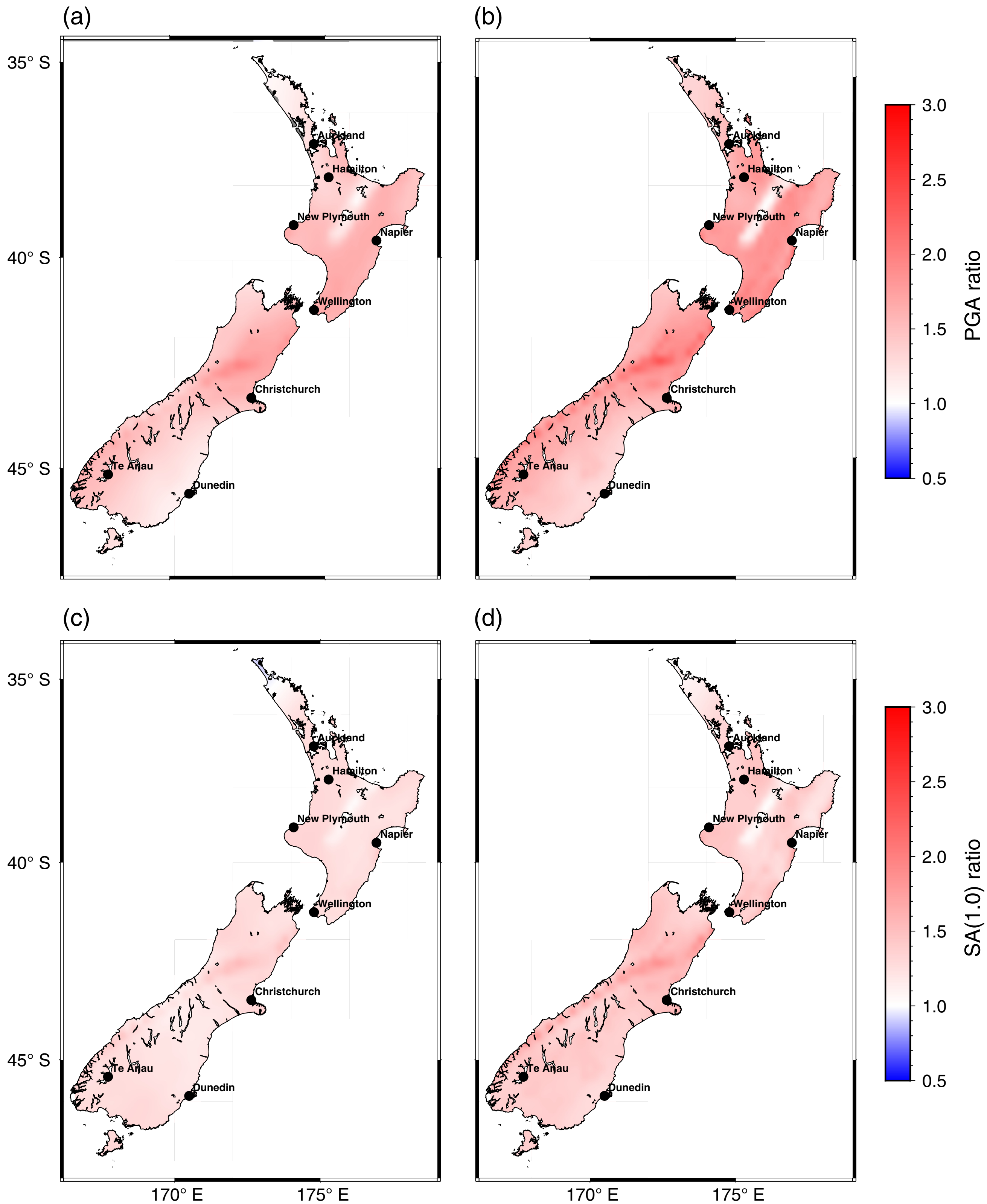


Figure 9. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau for $V_{S30} = 250$ m/s. (a,c,e,g) Comparisons for PGA. (b,d,f, h) Comparisons for SA (1 s). Here SRM-2010 stands for seismicity rate model in NZ NSHM 2010, and GMCM-2022 (full) stands for ground-motion model characterization modeling (GMCM) 2022 with full logic trees for all SC, SI, and SS sources. GMCM-2022 (SC + SI) means the GMCM-2022 logic tree with only SC and SI GMMs updated while SS GMMs identical to GMCM-2010. The color version of this figure is available only in the electronic edition.



(2022, 2024), the GMMs of KBCG20, PSBAH22, and A22 do not account for such reduction in σ due to predictor variable dependence toward lower V_{S30} values. Keep in mind that the dominant site condition across major urban centers in NZ is very soft to soft soil (V_{S30}: 200–400 m/s; Wotherspoon *et al.*, 2022, 2024). Thus, such a adjustment in σ models of

Figure 10. Hazard ratio maps. The ratios are computed for $V_{S30} = 250$ m/s as hazard when only SC GMMs are updated (SI and SS GMMs being the same as in GMCM-2010) to hazard with NZ NSHM 2010. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

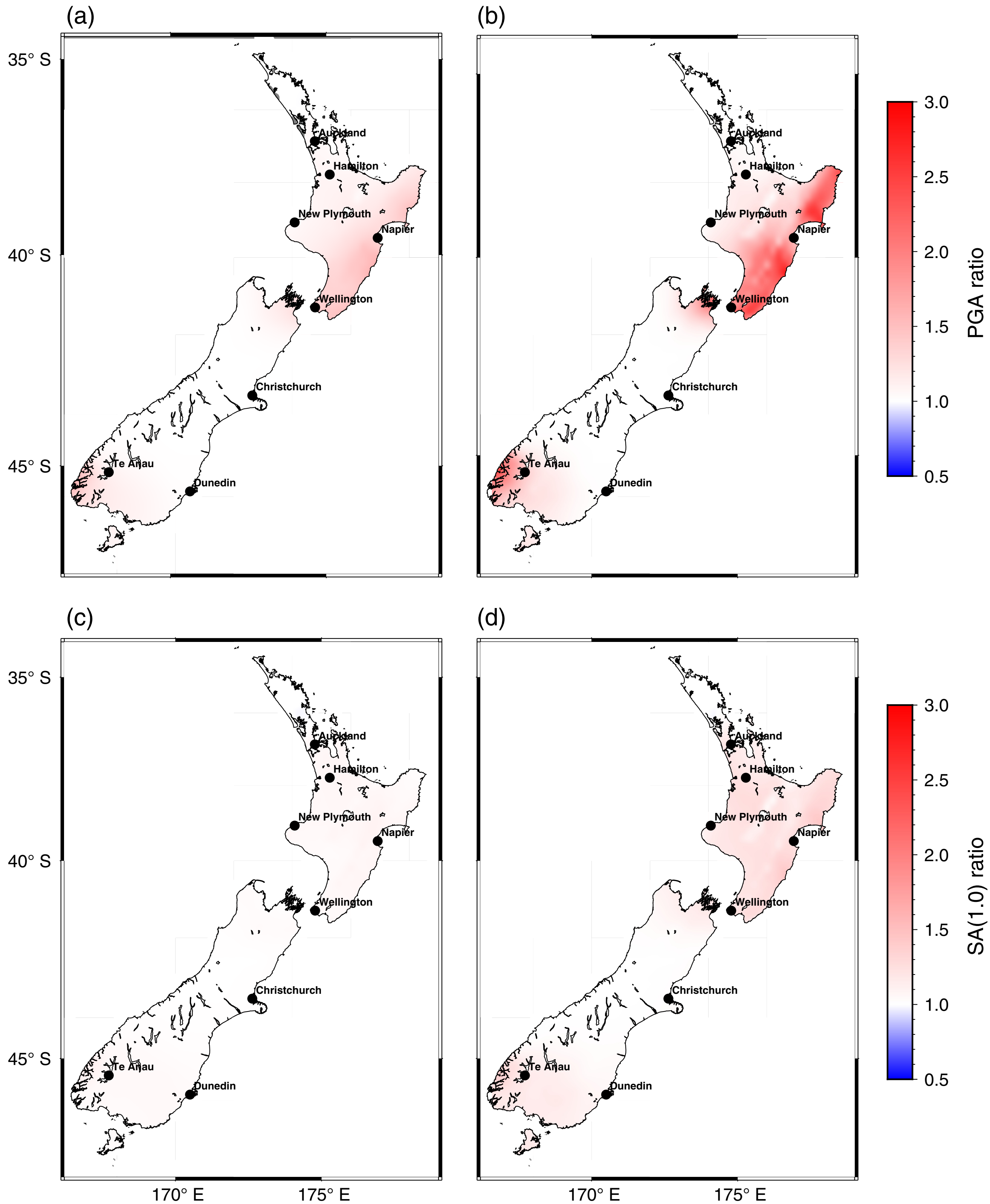


Figure 11. Hazard ratio maps. The ratios are computed for $V_{S30} = 250$ m/s as hazard when only SI GMMs are updated (SC and SS GMMs being the same as in GMCM-2010) to hazard with NZ NSHM 2010. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

aforementioned GMMs was considered appropriate. Figure 14 depicts full hazard curves at four locations: Auckland, Wellington, Christchurch, and Te Anau with the highest weighted branch from SRM-2022 as the source characterization model. As expected, such adjustments mainly affect PGA and other shorter period IMs (not shown here). In

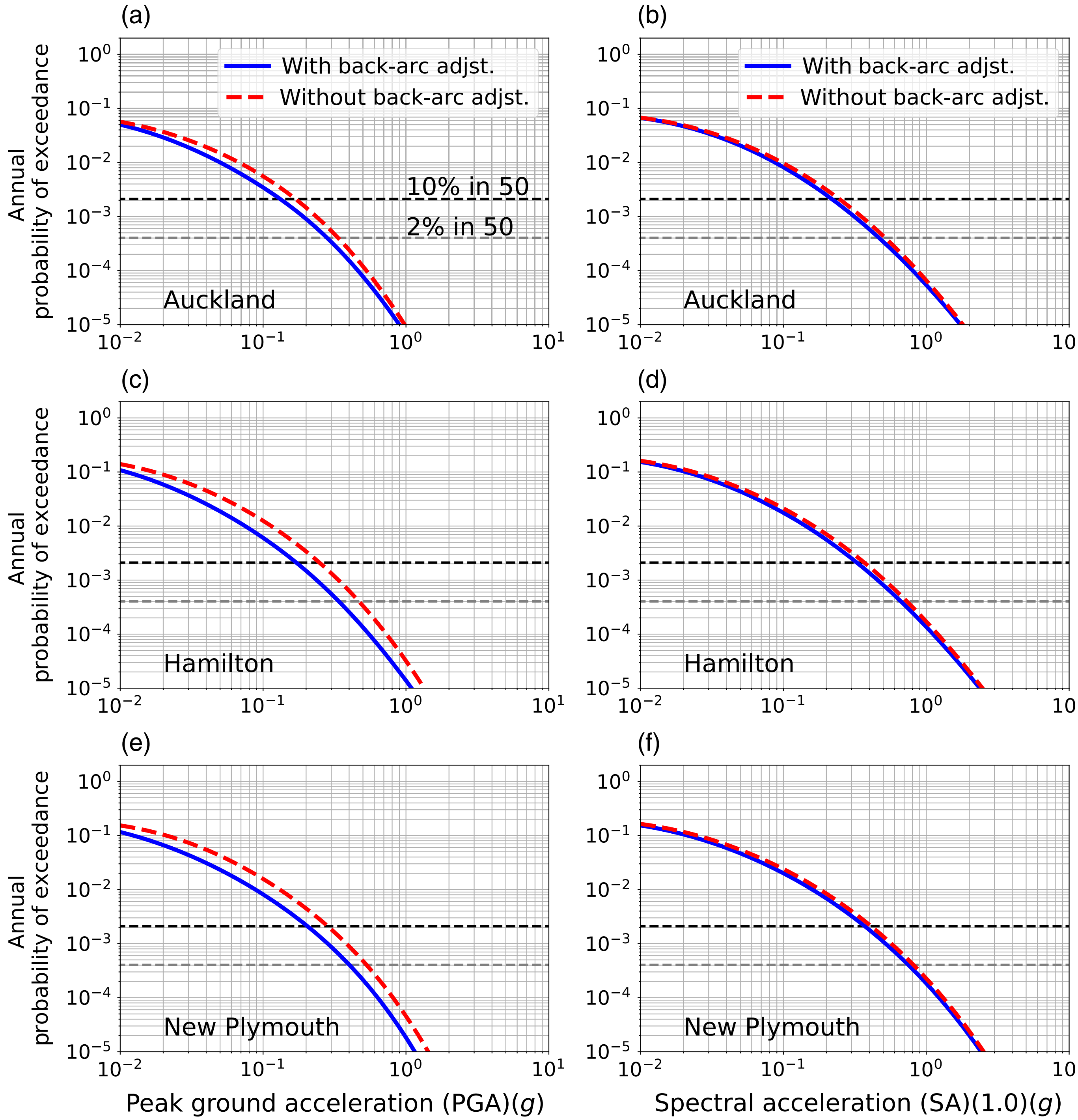


Figure 12. Hazard curves comparisons at Auckland, Hamilton, and New Plymouth. (a,c,e) Comparisons for PGA. (b,d,f) Comparisons for SA (1 s). The comparisons are shown for $V_{S30} = 250$ m/s between GMCM-2022 with and without back-arc adjustments in SS GMMs keeping SRM-2022 common. The color version of this figure is available only in the electronic edition.

addition, the impact is seen toward smaller APoEs that essentially reflects the larger magnitude scenarios and associated occurrence rates and the manner in which the σ of GMM affects hazard.

The ratios are computed at each grid point as: $\mathrm{IM}_{\mathrm{NL}-\sigma}/\mathrm{IM}_{\mathrm{Published}-\sigma}$ for 10% and 2% PoE in 50 yr. Thus, as also noted in the previous section, such ratios directly express the fractional reduction in hazard as an outcome of such adjustments in the GMMs of KBCG20, PSBAH22, and A22. Figure 15 shows the ratios maps with the highest weighted branch of SRM-2022 as the source characterization model used to compute hazard. As also indicated in Figure 14, the main impact of these corrections is for 2% PoE in 50 yr, and mostly concentrated toward northeastern part of the North Island and southwestern part of the South Island—the regions dominated

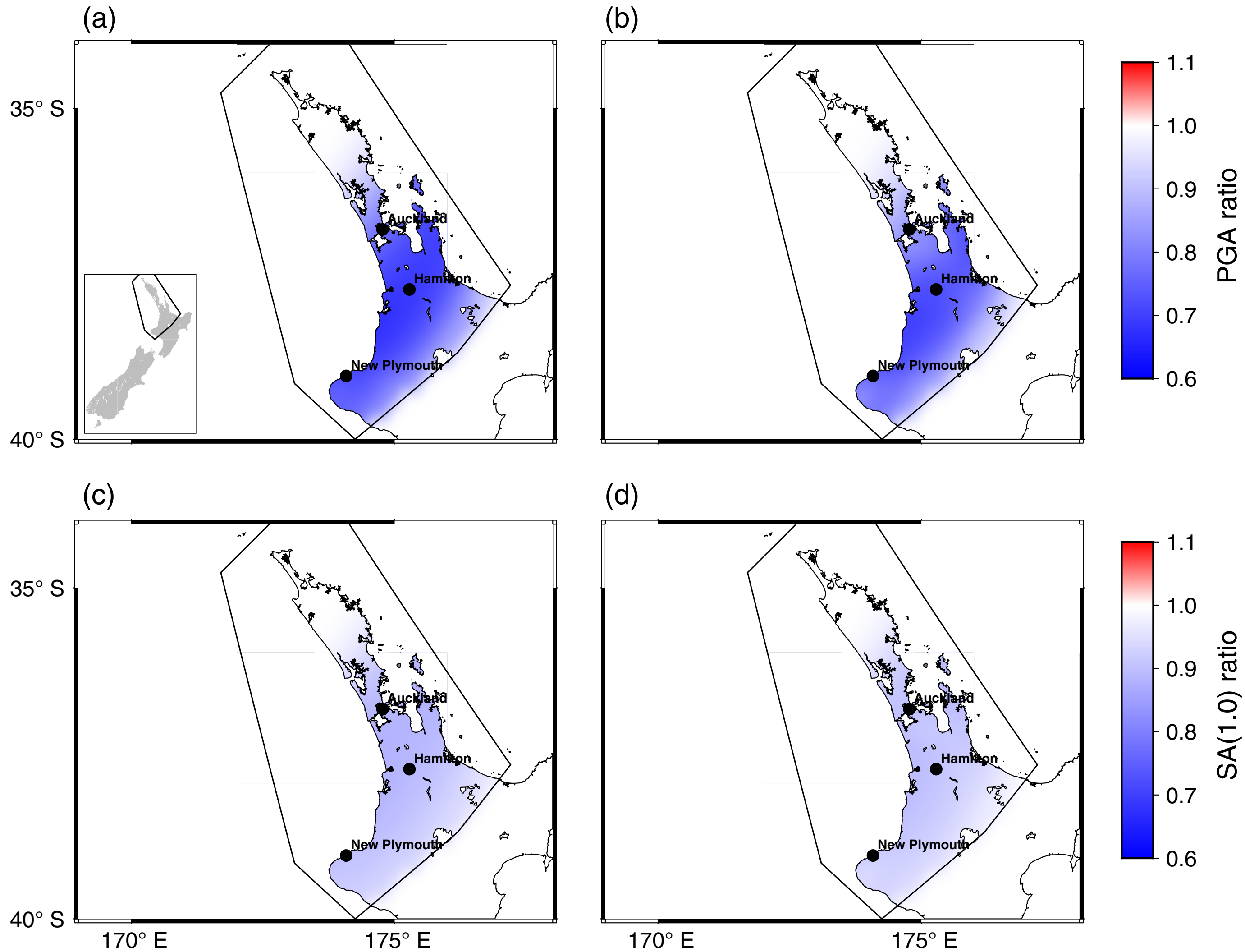


Figure 13. Hazard ratio maps. The ratios are computed as hazard with back-arc adjustments to hazard without back-arc adjustment in SS GMMs for GMCM-2022. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The ratio maps are shown for $V_{S30} = 250$ m/s and using SRM-2022. The polygon on top of each plot shows the boundaries of the back-arc region. The color version of this figure is available only in the electronic edition.

by SI seismicity. It is worth mentioning here that these ratio maps are shown for uniform V_{S30} of 250 m/s over the entire country (at each grid point); in practical situations, the V_{S30} may vary on a local scale. Hence, impact of these adjustments depends upon the local soil conditions, as illustrated in Kaiser *et al.* (2022, 2024). The impact of nonlinear soil response adjustments with SRM-2010 as the source characterization model is presented in terms of hazard curves and hazard ratio maps in the supplemental material.

Effect of uniform versus nonuniform GMC logic-tree weights

In this subsection, we illustrate the impact of GMCM logic-tree weights on the final hazard results. For that purpose, two sets of hazard calculations were performed with the highest single SRM-2022 branch using the identical GMCM-2022 logic-tree structure but with two different sets of weights for each GMM within SC, SI, and SS logic trees: (1) weights based on expert elicitation (Gerstenberger, Bora, *et al.*, 2022); and (2) uniform weights on each GMM. The uniform weights were applied only to the consideration of alternative GMMs, and the weights on the within-model epistemic uncertainty were set to to 0.3, 0.4, and 0.3 corresponding to upper, central, and lower branches (of each GMM block), respectively. Comparisons of the hazard results are performed both in terms of ratios maps and comparison of full hazard curves. However, only ratios maps are presented here in Figure 16 and the comparison of hazard curves are presented in the supplemental material. Figure 16 shows the ratio maps for 10% PoE in 50 yr and 2% PoE in 50 yr. The ratios at each grid point are computed with hazard from uniform GMCM weights in the denominator, making it the reference base. In that case, the ratios essentially represent the relative fractional change in hazard against a uniform weighting scheme. Clearly, the differences are not significant

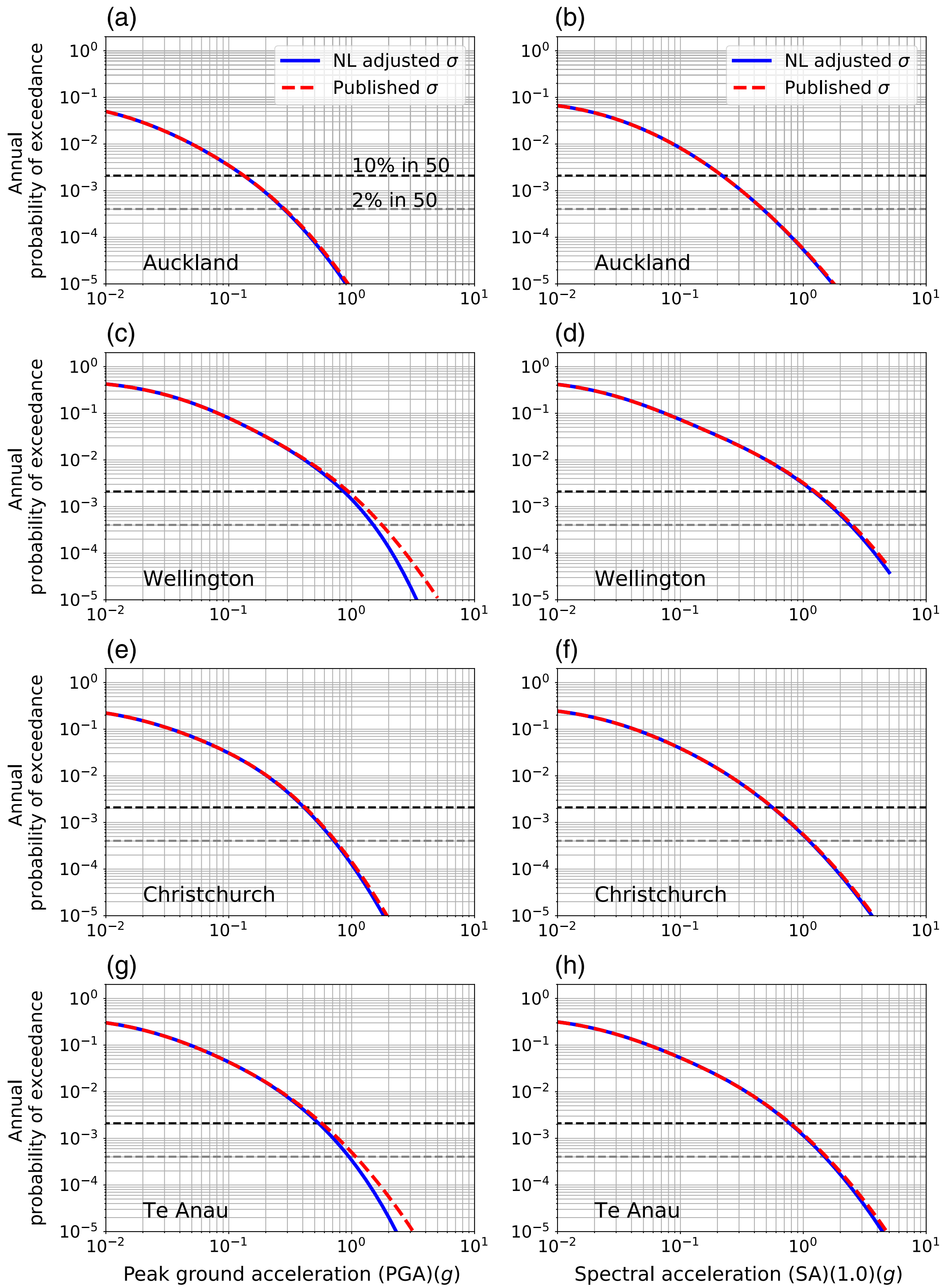


Figure 14. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau. (a,c,e,g) Comparisons for PGA. (b,d,f,h) Comparisons for SA (1 s). The comparisons are shown for $V_{S30} = 250$ m/s between GMCM-2022 with and without nonlinear soil response correction in aleatory uncertainty (σ) and using the highest weighted branch from SRM-2022. The color version of this figure is available only in the electronic edition.

and range between 0% and 5% depending upon the location. Interestingly, the (geographical) variation of the differences for SA (1 s) is opposite to that for PGA except in the vicinity of Alpine fault. Such behaviors are affected by the sources that dominate hazard at that location and that how the (magnitude and distance) scaling at various oscillator periods behaves

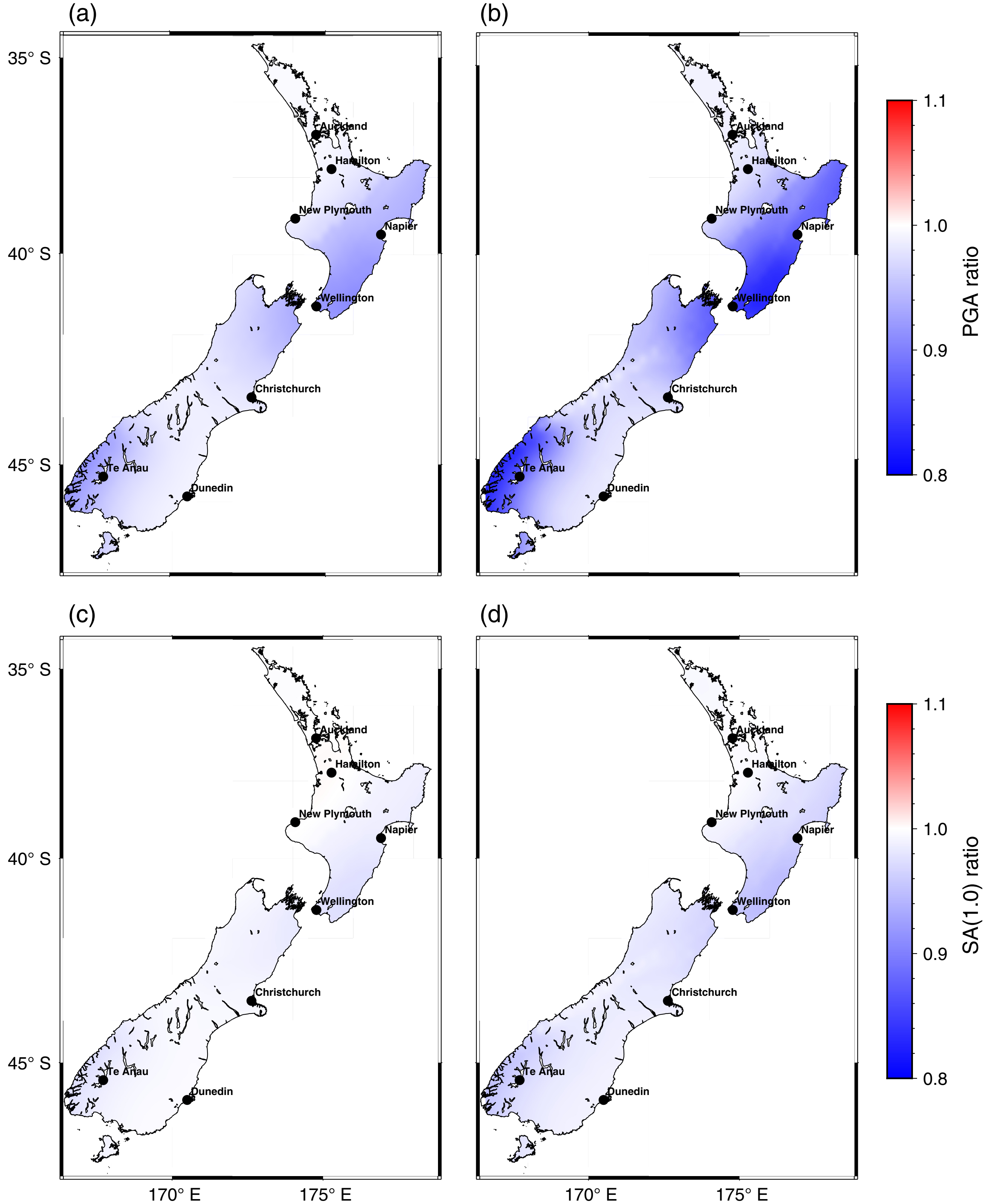


Figure 15. Hazard ratio maps. The ratios are computed as hazard when nonlinear soil response adjustments were made in aleatory uncertainty (σ) models of KBCG20, PSBAH22, and A22 GMMs to hazard when no such adjustments were made in these GMMs. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The ratio maps are shown for $V_{S30} = 250$ m/s and using SRM-2022. The color version of this figure is available only in the electronic edition.

between different types of GMMs. Disaggregation plots provided in the supplemental material show the dominant rupture scenarios at eight selected major locations. The rather smaller impact of logic-tree weights on hazard can also be attributed to the large epistemic uncertainty captured by the upper and lower branches of S22 GMM.

Effect of global GMMs versus NZ-specific GMMs

So far, we have discussed the impact of various modelling choices on hazard results considering the logic-tree structure (and GMMs) of GMCM-2022. In this subsection, we investigate the effect of various GMM combinations (effectively logic-tree choices) on the final hazard results. Specifically, we evaluate the relative impact of global GMMs (NGA-West2 and NGA-Sub) compared with if only NZ-specific GMMs (B13, A22, and S22) are considered for the GMCM logic tree. We reiterate that these GMMs are also anchored on global GMMs with adjustments made using NZ data to account for differences in magnitude and distance scaling. An additional result is presented with hazard calculated using only the two recently derived NZ-specific backbone GMMs to evaluate their impact, given that they are calibrated on a recently compiled database. Thus, using the same highest weighted SRM-2022 branch at sites with $V_{S30} = 250$ m/s, the hazard calculations were performed for the three choices of GMCM logic trees: (1) only global GMMs, that is, ASK14, BSSA14, CB14, and CY14 for SC sources and AG20, KBCG20, and PSBAH22 for SI and SS source; (2) only NZ-specific GMMs, that is, B13, A22, and S22 for SC sources and only A22 for SI and SS sources; (3) only recently derived backbone GMMs of A22 and S22 for SC sources, and only A22 for SI and SS sources. A uniform weighting scheme is applied in all the three cases. Moreover, the additional NZ-specific adjustments to the published GMMs—accounting for back-arc attenuation and nonlinear soil response in aleatory uncertainty—made specifically within NZ NSHM 2022 were kept common for the three cases. Figure 17 shows hazard curves for the three cases at four major locations: Auckland, Wellington, Christchurch, and Te Anau. For comparison, the hazard curves from GMCM-2022 logic tree (with uniform weights) are also shown. The same plots for Hamilton, Napier, New Plymouth, and Dunedin are shown in the supplemental material. Clearly, in low-hazard regions such as Auckland, Christchurch, New Plymouth, and Dunedin, the choice of alternate GMMs have no impact on hazard for PGA, while the NZ-specific GMMs result in slight increase in hazard for SA (1 s). In addition, these are the locations dominated by crustal sources (see Fig. 5). On the other hand, in high-hazard regions, such as Wellington, Te Anau, and Napier, the global GMMs result in higher hazard for PGA and in lower hazard for SA (1 s) in comparison with NZ-specific GMMs. In some cases, the impact is significant; for example, the SA (1 s) amplitude at 2% PoE in 50 yr in Wellington is a factor of two larger if using NZ-specific (or the two backbone GMMs) GMMs, in comparison with the result for the global GMMs. Relatively larger differences for SA (1 s) toward lower APoEs indicate differences in magnitude scaling toward larger magnitude events. The differences in PGA hazard curves at Wellington, Te Anau, and Napier can be attributed to differences in both magnitude scaling as well as in regional attenuation. In addition to the median GMM scaling plots, the disaggregation plots at the locations mentioned earlier are provided in the supplemental material.

DISCUSSION

The update in GMCM scheme for NZ NSHM 2022 represents a major change with respect to the penultimate NZ NSHM 2010. Prior to the release of the NZ NSHM 2022, numerous hazard sensitivity analyses were carried out both in GMCM and SRM space. In this article, we have presented hazard sensitivities mainly with respect to the GMCM scheme adopted in NZ NSHM 2010 and NZ NSHM 2022 along with the impact of NZ-specific adjustments to some of the published GMMs. However, such sensitivities are contingent on the source characterization model used. Moreover, inclusion of the two NZ-specific adjustments—back-arc attenuation adjustment and nonlinear soil response adjustment in σ—were motivated by observing hazard results with the combination of SRM-2022 (the highest weighted branch) and GMCM-2022. Hence, the impact of SRM sensitivities, using a single SRM branch from SRM-2022, is also presented. The hazard sensitivities with respect to SRM choice, that is, SRM-2010 and SRM-2022, were presented using GMCM-2022. Clearly, these sensitivities do not show the full impact of the full SRM-2022 logic-tree branch, but they provide direction of the relative change due to SRM changes in relation to GMCM changes. This clearly showed us in which regions the GMCM changes account the most for the observed hazard change with respect to NZ NSHM 2010. Further dissection of SRM hazard sensitivities is beyond the scope of this article, and reader is referred to Gerstenberger, Bora, *et al.* (2023) and Gerstenberger, Van Dissen, *et al.* (2023) for detailed discussion on this topic.

The increase in mean hazard with respect to NZ NSHM 2010 by just updating the GMCM-2022 can be mainly attributed to both: (1) larger median of the NGA-West2 and NGA-Sub models in comparison with the McV06 GMM; and (2) larger aleatory uncertainty (σ) of these models particularly of NGA-Sub models (see figures in the supplemental material). However, the impact of σ is rather pronounced toward smaller APoEs. In addition, relatively larger impact of the update in SC GMMs in comparison with the update in SI GMMs is rather intriguing. With other factors considered, such as dominant rupture scenarios in SRM-2010, we mostly attribute this to the differences in magnitude scaling between the recent NGA-Sub models and McV06 GMM (see figures in the supplemental material). The impact of updated GMCM-2022 logic tree was further dissected in terms of relative impact of global GMMs (NGA-West2 and NGA-Sub) against the NZ-specific GMMs. Major differences, mainly toward lower APoEs, were observed in high-hazard regions dominated by subduction sources such as Wellington, Napier, and Te Anau. The differences in calculated hazard were insignificant in low-hazard regions dominated by crustal sources such as Auckland, Christchurch, New Plymouth, and Dunedin.

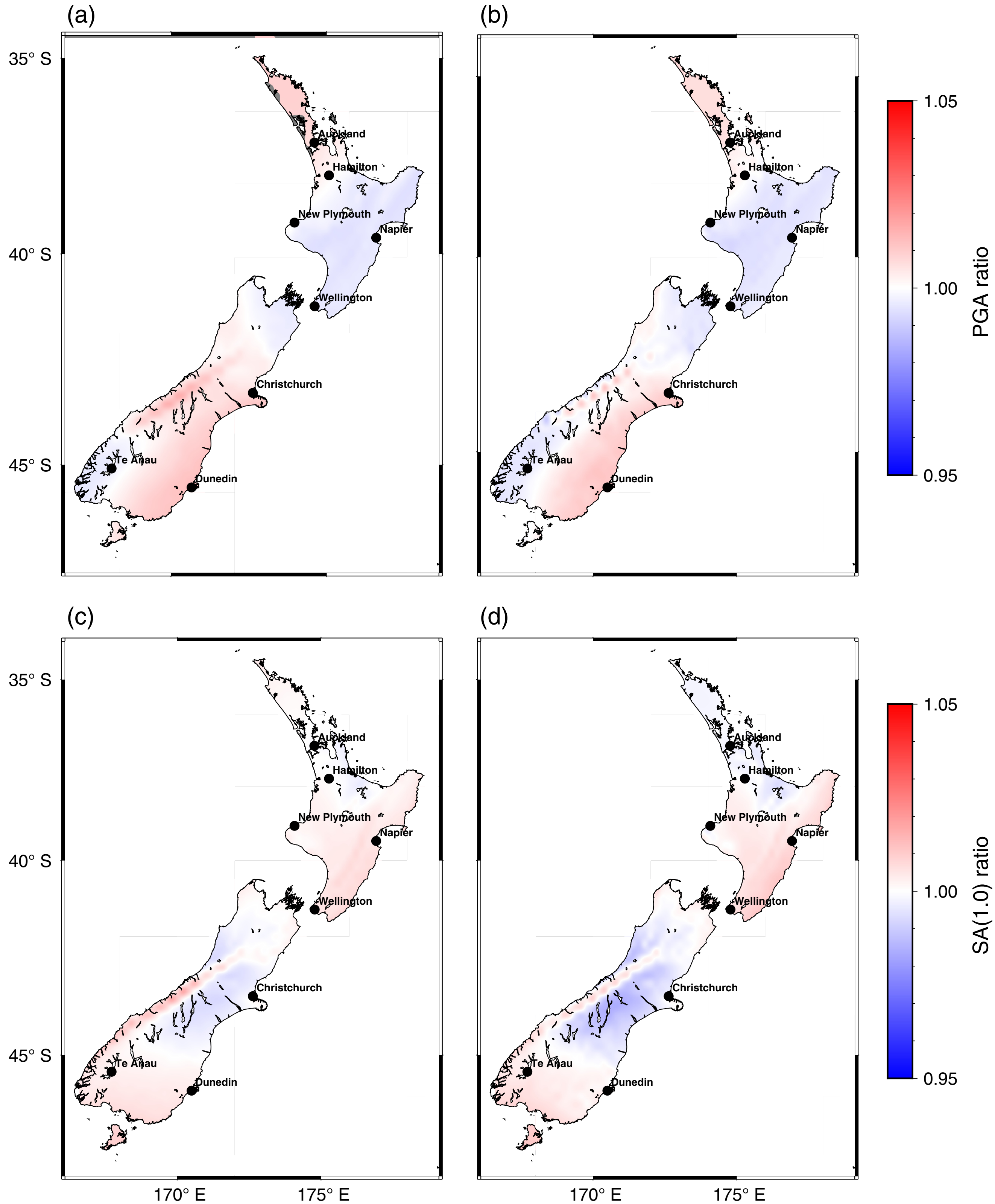


Figure 16. Hazard ratio maps. The ratios are computed as hazard with expert judgement based weights for GMCM-2022 to hazard with uniform weights. (a,c) The ratios for 10% PoE in 50 yr. (b,d) The ratios for 2% PoE in 50 yr. The ratio maps are shown for $V_{S30} = 250$ m/s and using SRM-2022. The color version of this figure is available only in the electronic edition.

Major trends from the sensitivity analysis, presented here with respect to various components, are summarized in Figures 18 and 19 for Auckland and Wellington (see Fig. 1). Such plots for other locations: Hamilton, Napier, New Plymouth, Christchurch, Dunedin, and Te Anau are presented in the supplemental material. These plots show ratios with NZ NSHM

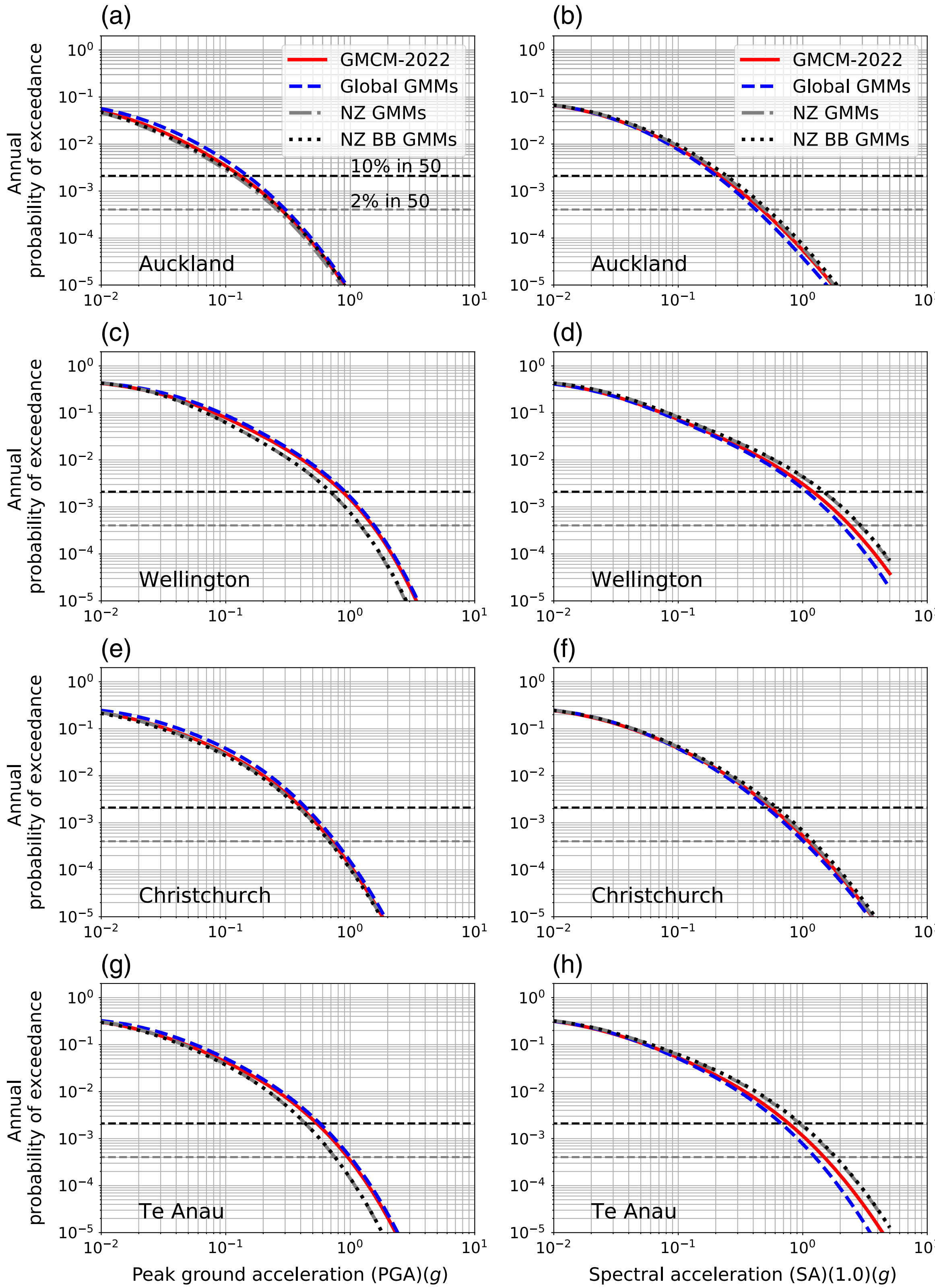


Figure 17. Hazard curves comparisons at Auckland, Wellington, Christchurch, and Te Anau. (a,c,e,g) Comparisons for PGA. (b,d,f,h) Comparisons for SA (1 s). The comparisons show impact of global GMMs versus NZ-specific GMMs along with hazard curves from NZ-specific backbone GMMs only. The comparisons are shown for $V_{S30} = 250$ m/s and using the highest weighted branch from SRM-2022. Also note that the hazard curves are shown with the uniform weights on GMCM logic-tree branches in all the four cases. The color version of this figure is available only in the electronic edition.

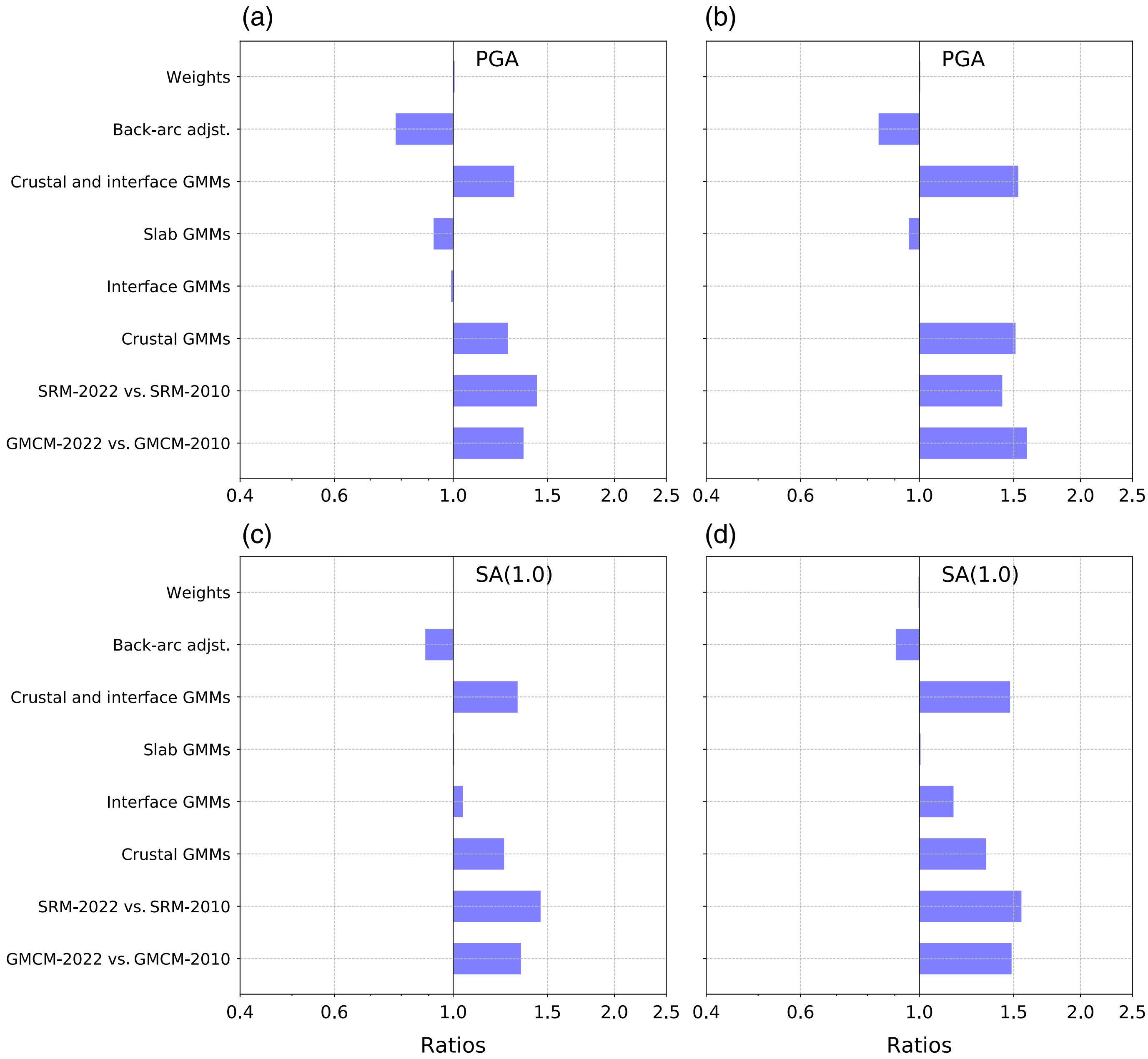


Figure 18. Plots showing relative size and direction of hazard sensitivities for different components at Auckland corresponding to PGA, SA (1 s). (a,c) Hazard sensitivities for 10% PoE in 50 yr. (b,d) Hazard sensitivities for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

2010 as reference (i.e., in the denominator) for GMCM sensitivities, whereas for NZ-specific adjustments GMCM-2022 without these adjustments are considered as reference. For weight sensitivities, GMCM-2022 logic tree with uniform weights is considered as reference. In addition, the back-arc adjustments were performed for only sites in the back-arc region. Similarly, the nonlinear soil response adjustment in σ had least impact in low-hazard regions such as Auckland, Christchurch, and Dunedin. Essentially, there were no regions in NZ that were significantly affected by the simultaneous effect of both—the back-arc attenuation adjustment and nonlinear soil response adjustment in σ. The key observations from these figures can be summarized as follows:

1. Effect of SRM change is dominant (or driver of the change in hazard) mainly in low-hazard regions: Auckland, Hamilton, New Plymouth, and Dunedin. In Christchurch, the changes in SRM and GMCM contribute equally to the change in hazard.
2. Effect of GMCM change is dominant in high-hazard regions such as: Wellington, Napier in the North Island, and Te Anau in the South Island.
3. Effect of tectonic type (GMM) dominate mostly:
   - SI for locations along the east cost of North Island (Napier and Wellington), Marlborough Sounds, and lower west coast of South Island, Fiordland, and Te Anau.

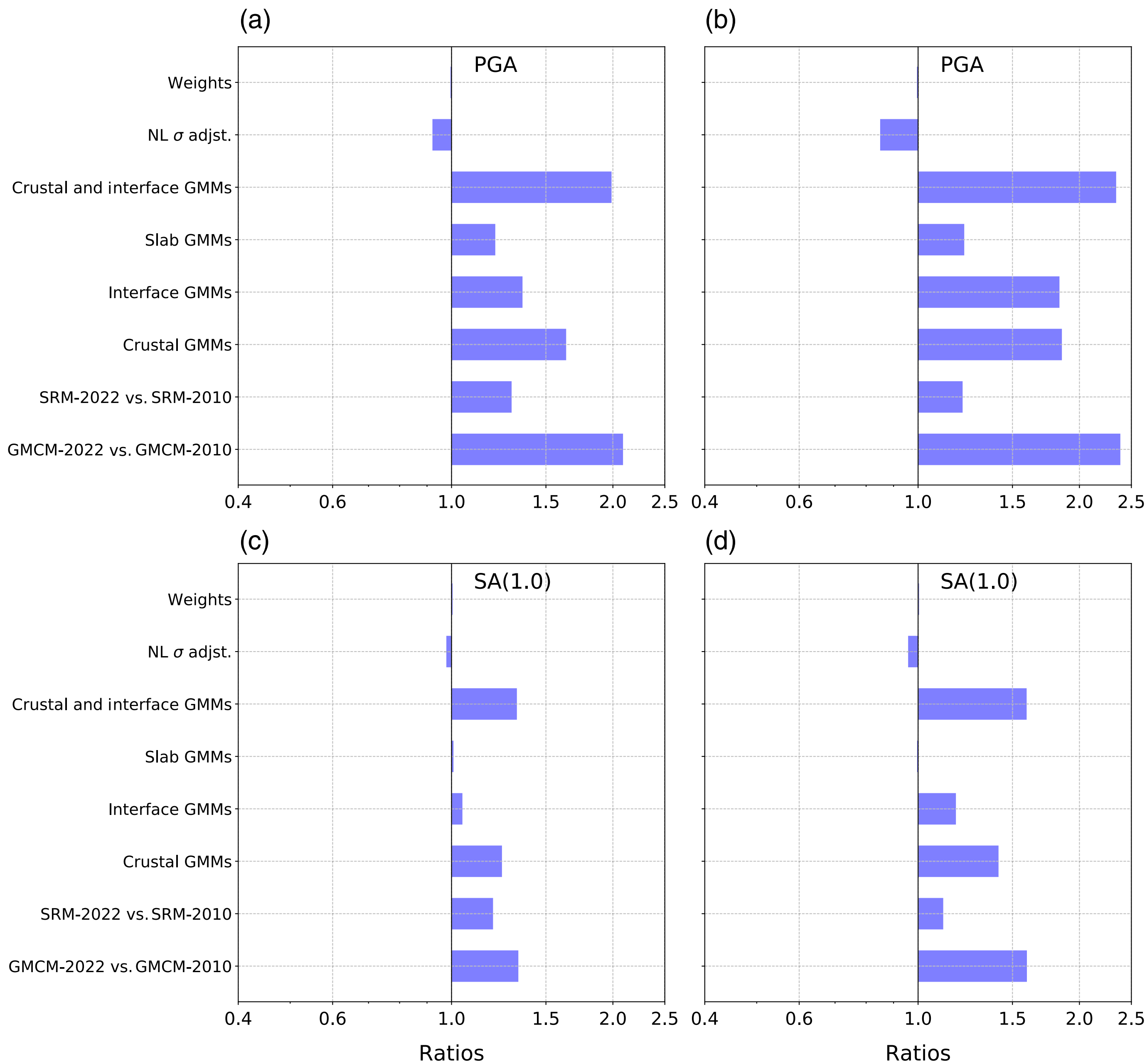


Figure 19. Plots showing relative size and direction of hazard sensitivities for different components at Wellington corresponding to PGA, SA (1 s). (a,c) Hazard sensitivities for 10% PoE in 50 yr. (b,d) Hazard sensitivities for 2% PoE in 50 yr. The color version of this figure is available only in the electronic edition.

- SC dominant across majority of NZ compounded by subduction changes for eastern-north part of the North Island.

4. NZ-specific adjustments:
   - Back-arc adjustments accounts for 30%–40% reduction (for PGA) in northwestern part of North Island, Auckland, Hamilton, and New Plymouth. The effect is less at longer periods.
   - Nonlinear soil response adjustment in σ accounts for 10%–20% reduction (for PGA; less so for longer periods) in high-hazard regions such as Wellington, Napier, and Te Anau.
5. No significant impact of weights to the GMCM logic-tree branches, typically only up to 3%–4% across entire NZ.
6. Relative impact of global GMMs versus NZ-specific GMMs: only in high-hazard regions (Wellington, Napier, and Te Anau) the PGA hazard is estimated to be higher from global GMMs while lower for SA (1 s). In low-hazard regions such as Auckland, Christchruch, New Plymouth, and Dunedin the differences were insignificant.

CONCLUSIONS

In this article, we have presented results of hazard sensitivity analysis associated with the GMCM scheme of NZ NSHM 2022. A major change in GMCM-2022 with respect to NZ

NSHM 2010 is the use of a hybrid modeling approach that combines a weights on models approach with backbone modeling framework. In particular, two backbone models are included for SC and one each for SI and SS sources. In addition, for crustal seismicity, four NGA-West2 models along with a NZ-adjusted GMM were used. Similarly, for subduction seismicity, along with the NZ-adjusted backbone model, three NGA-Sub GMMs were used. Replacing GMMs from NZ NSHM 2010 by GMCM-2022 results in a overall change in calculated hazard across entire NZ and, 1.5–2.5 times increase along the east coast of North Island depending upon the location and vibration period. For low-seismicity regions, such as the upper-western part of the North Island and the lower-eastern part of the South Island the major change in calculated hazard comes from the source characterization models. In terms of tectonic type, the change in SC GMMs accounts for the major change throughout the country which is further compounded by the change in SI GMMs for east coast of the North Island. Adjustments for back-arc attenuation (in median models) and soil nonlinear response (in σ models) accounts for 30%–40% reduction in hazard for northwest and 10%–20% for east coast of the North Island, respectively.

DATA AND RESOURCES

All data used in this article came from published sources listed in the references except the hazard calculations. The hazard calculations presented in this article were performed using OpenQuake engine from global earthquake model (GEM) foundation. All the plots were created in Python using open source libraries. The supplemental material includes figures related to: (1) comparison plots of median and aleatory uncertainty models for all the considered ground-motion models in New Zealand National Seismic Hazard Model (NSHM) 2022; (2) schematic of logic trees; (3) comparison plots of hazard curves and hazard ratio maps; (4) tornado plots showing relative sensitivities; and (5) disaggregation plots from NZ NSHM 2010 and NZ NSHM 2022 for selected locations.

DECLARATION OF COMPETING INTERESTS

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

ACKNOWLEDGMENTS

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