# New Zealand National Seismic Hazard Model Revision 2022: Hazard Changes with respect to NZ NSHM 2010

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## ABSTRACT

The 2022 revision of New Zealand National Seismic Hazard Model (NZ NSHM 2022) represents a significant change not only in hazard results but also in terms of methods and processes in comparison to NZ NSHM 2010. The changes span over every component of the entire model including significant changes to the seismicity rate model (SRM), and the ground-motion characterization model (GMCM) including modelling of site-effects. One important change is quantification of the plausible range of epistemic uncertainty in hazard estimates. This is achieved by using multiple (alternate) models within the full SRM and GMCM logic trees.

In this paper, we present a systematic comparison of hazard results from NZ NSHM 2022 against those from NZ NSHM 2010. Specifically, we illustrate the impact resulting from changes in the GMCM and SRM individually. Additionally, the comparisons are elucidated in terms of hazard sensitivities with regard to specific modelling and parameter choices in the GMCM and SRM.

Our results show that on average the shaking hazard increases by a factor of 1.5-2.0 depending upon the vibration period and location across the country. In high hazard regions such as the eastern part of the North Island change in the GMCM dominate the change in hazard while in low hazard regions (the north-western part of North Island and the south-eastern part of the South Island) change in the SRM dominate the change. These changes are further dissected in terms of changes originating from different source types (or tectonic types) both in ground-motion characterization and seismicity rate models.

## 1 INTRODUCTION

The recent 2022 revision of New Zealand National Seismic Hazard Model (NZ NSHM 2022) represents a major revision of the NZ NSHM across all model 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. Specifically, NZ NSHM 2022 involves significant changes both in modelling scheme and parameter choices such as modelling of seismogenic fault sources in the seismicity rate model (SRM) component, use of multiple ground-motion models (GMMs) in the ground-motion characterization modelling (GMCM) component, and using time-averaged shear wave velocity in upper 30m ($V_{S30}$) as the site parameter to account for the local site-effects.

Figure 1 shows the PGA hazard map for 10% probability of exceedance (PoE) in New Zealand along with mapped active fault traces from the recent revision (Gerstenberger et al., 2022; 2023). Evidently, the PGA hazard values from NZ NSHM 2022 are high along the eastern margin of North Island proximal to the Hikurangi subduction zone and along the Alpine fault in the South Island. One may also observe the impact of Puysegur subduction zone towards the southwestern portion of the South Island. As summarized by Gerstenberger et al. (2022; 2023) the increase in ground shaking hazard amounts to (on average) 1.5-2.5 times to that of from NZ NSHM 2010 depending upon geographical location, spectral vibration period and the site condition.

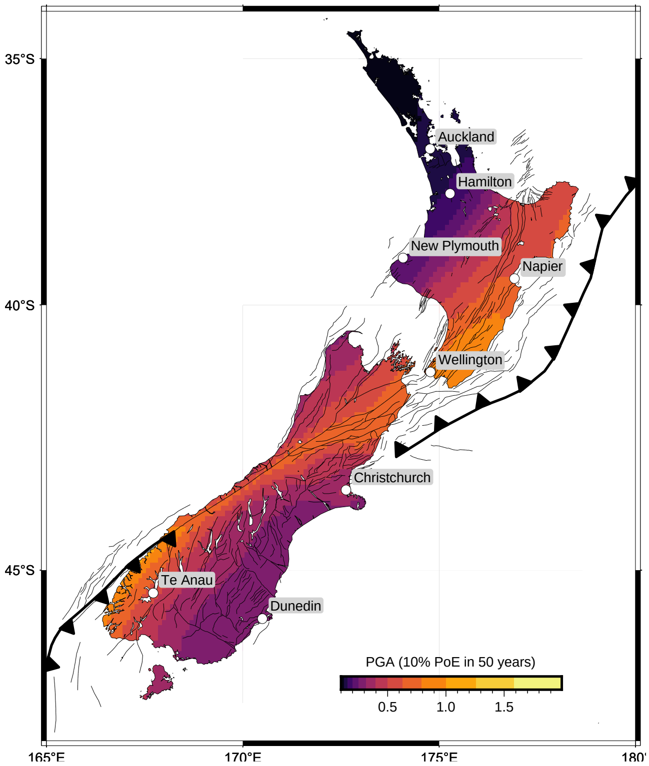


*Figure 1 Peak ground acceleration (PGA) hazard map for 10% probability of exceedance in 50 years from NZ NSHM 2022 (Gerstenberger et al., 2022) along with the locations of major towns considered for hazard sensitivity analysis in this article. The grey shaded regions show two subduction zones Hikurangi-Kermadec (proximal to north-east of North Island) and Puysegur (proximal to south-west of South Island).*

In this study we detail the changes in seismic hazard across New Zealand with respect to NZ NSHM 2010. In particular, we highlight the changes driven by the updates in two main model components, that is, updates in the SRM and GMCM. The organization of the article is as follows: 1) first we provide a brief summary of the hazard model components that are examined in this study, 2) second, we compare the total change in hazard from the full update of the hazard model with respect to NZ NSHM 2010, and 3) in subsequent sections, we further dissect the changes in terms of updates make to individual model components of the SRM and GMCM.

## 2 BRIEF SUMMARY OF HAZARD MODEL COMPONENTS EXAMINED

### 2.1 Seismic source Characterization

The two SRMs—hereafter referred to as SRM-2010 and SRM-2022—used in the present analysis are briefly discussed below; however, detailed discussion and comparison of the two source models is beyond the scope of this article.

### 2.1.1 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 faults to develop a single characteristic earthquake sources in terms of magnitude and frequency for each identified fault source. The fault source model accounts for most of the large events with **M** > 7 over mapped crustal faults and **M** > 8 for subduction zones. The DSM adopts a zone based SRM to account for the observed seismicity across NZ for events **M** > 5. Rates of such events are constrained using conventional Gutenberg-Richter magnitude-frequency analysis for each zone.

### 2.1.2 SRM-2022

The SRM-2022 is composed of two main building blocks (Gerstenberger et al., 2023; Gerstenberger et al., 2024): 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 that are based on deformation models presented in Van Dissen et al. (2023). The DSM complements the IFM based on additional information such as recent and 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 (Iturrieta et al., 2024b, Rastin et al., 2024). To capture epistemic uncertainty, the SRM-2022 involves thirty six logic-tree branches for crustal sources, nine logic-tree branches for subduction interface sources and one single branch to model the subduction intraslab sources. For further details on SRM-2022, reader is referred to Gerstenberger et al. (2024).

## 2.2 Ground-motion characterization modelling

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

### 2.2.1 GMCM-2010

The NZ NSHM 2010 (Stirling et al., 2012) uses GMMs developed by McVerry et al. (2006) for 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 McVerry et al. (2006) model was calibrated on a dataset compiled across NZ up to the end of 1995. Moreover, the McVerry et al. (2006) GMM prescribes model parameters (or coefficients) for crustal, subduction interface and subduction intraslab separately. Site-effects are modelled in terms of NZ-specific site subsoil classes and results are derived for the larger of the two horizontal components. Separate model coefficients were also provided for Taupo Volcanic Zone (TVZ).

It is worth mentioning here that the McVerry et al. (2006) GMM, adopted in GMCM-2010, is calibrated on the larger of the two horizontal components while 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 McVerry et al. (2006) to convert to equivalent RotD50 values.

### 2.2.2 GMCM-2022

The NZ NSHM 2022 adopts a hybrid modelling approach to capture the plausible range of epistemic uncertainty that combines a weights on the models approach with a backbone modelling framework. Lee et al. (2023) 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 Bradley et al. (2023). The 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 (Atkinson 2022; Stafford 2022; Bradley 2013) adjusted to NZ specific magnitude and distance scaling. Note that the two recent GMMs of Atkinson (2022) and Stafford (2022) are developed under the backbone ground-motion modelling framework with their inherent upper and lower branches defined to capture epistemic uncertainty.

For subduction sources (both interface and intraslab) the NZ NSHM 2022 GMCM adopted three recently derived NGA-Sub models: Abrahamson and Gulerce (2020), Kuehn et al. (2020) and Parker et al. (2022). In addition, ground-motion from subduction sources were modelled by Atkinson (2022). It is worth mentioning that Abrahamson and Gulerce (2020) and Kuehn et al. (2020) have developed NZ-specific regional models for subduction events which were not considered appropriate for hazard analysis after initial evaluation of the GMMs (Lee et al. 2023). The main reason for not including the NZ-specific regional models of Abrahamson and Gulerce (2020), Kuehn et al. (2020 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), 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 et al., 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 Bradley et al. (2023) which also provides detailed comparisons of median and aleatory uncertainty of the GMMs for different dominant scenarios.

For detailed discussion on the final GMCM logic tree for shallow crustal (SC), subduction interface (SI) and subduction intraslab (SS) reader is referred to the GNS report (Gerstenberger et al., 2022) and Gerstenberger et al. (2023).

## 2.3 Site effects

All the GMMs considered in the NZ NSHM 2022 GMCM parameterize site-effects using $V_{S30}$. All the crustal GMMs except Atkinson (2022) 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., 2023), 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 centres in NZ. The GMM used in NZ NSHM 2010, utilizes a NZ-specific site subsoil class approach to account for site-effects (Standards New Zealand 2024). 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. (2023) discuss this aspect, and also demonstrate that it can lead to considerable variability in site-specific hazard changes within a given urban area.

## 3 HAZARD CHANGES COMPARED TO NZ NSHM 2010

In this section, we demonstrate comparison of hazard changes between NZ NSHM 2022 and NZ NSHM 2010. First the full hazard changes are shown which are followed by discussing the impact of update in individual model components. Figure 2 shows the hazard ratio maps for 10% and 2% probability of exceedance (PoE) in 50 years for PGA Figure 3 shows the comparison of hazard curves at two major urban centres in New Zealand namely, Auckland and Wellington for PGA and spectral acceleration at 1s spectral period, (SA, 1s). In Figure 3, from NZ NSHM 2022, the 10$^{th}$ and 90$^{th}$ percentile hazard curves are also shown in addition to the mean hazard curves. Given that the NZ NSHM 2010 consisted of only a single SRM and a single GMCM hence it represents a single hazard estimate. It is evident from Figure 3 that at both the locations, Auckland (a relatively low hazard region) and Wellington (a relatively high hazard region), there is a significant increase in hazard with respect to NZ NSHM 2010 particularly for PGA. In fact, for low annual probabilities of exceedances (APoEs) of engineering interest, the ground-shaking from NZ NSHM 2010 is lower than the 10$^{th}$ percentile hazard curve from NZ NSHM 2022.

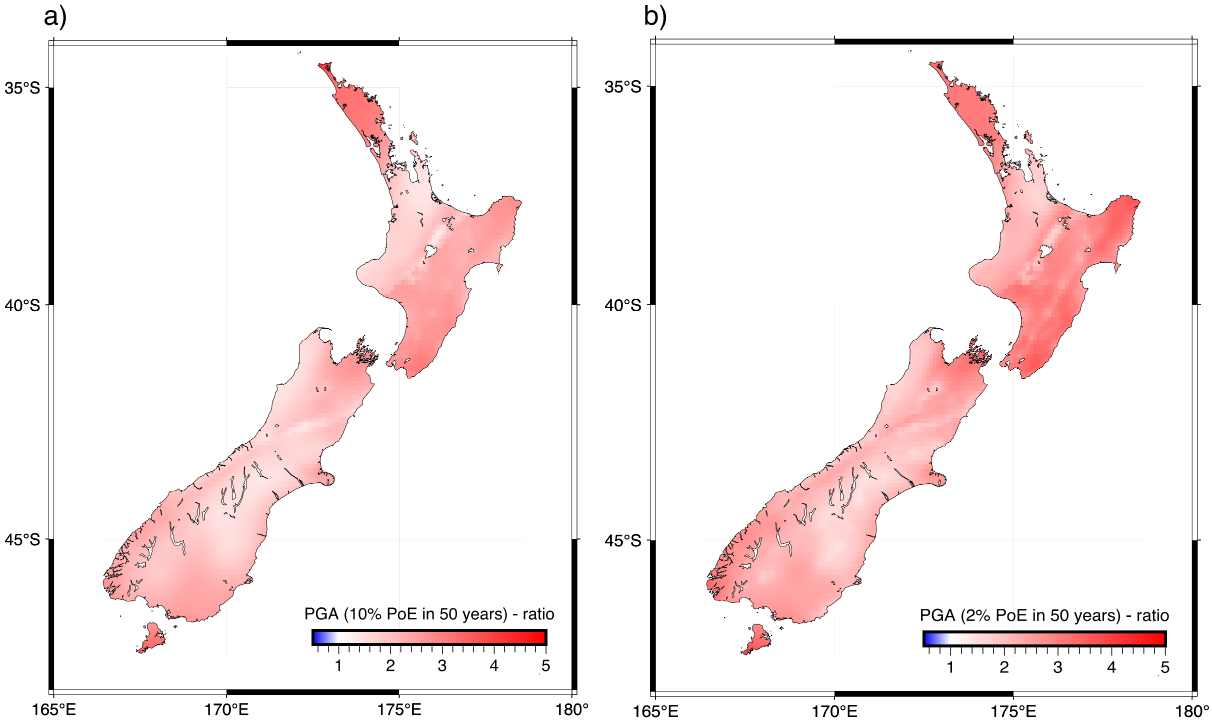


*Figure 2 Hazard ratio maps (NZ NSHM 2022/NZ NSHM 2010) for peak ground acceleration (PGA) for a) 10% probability of exceedance, and b) 2% probability of exceedance in 50 years.*

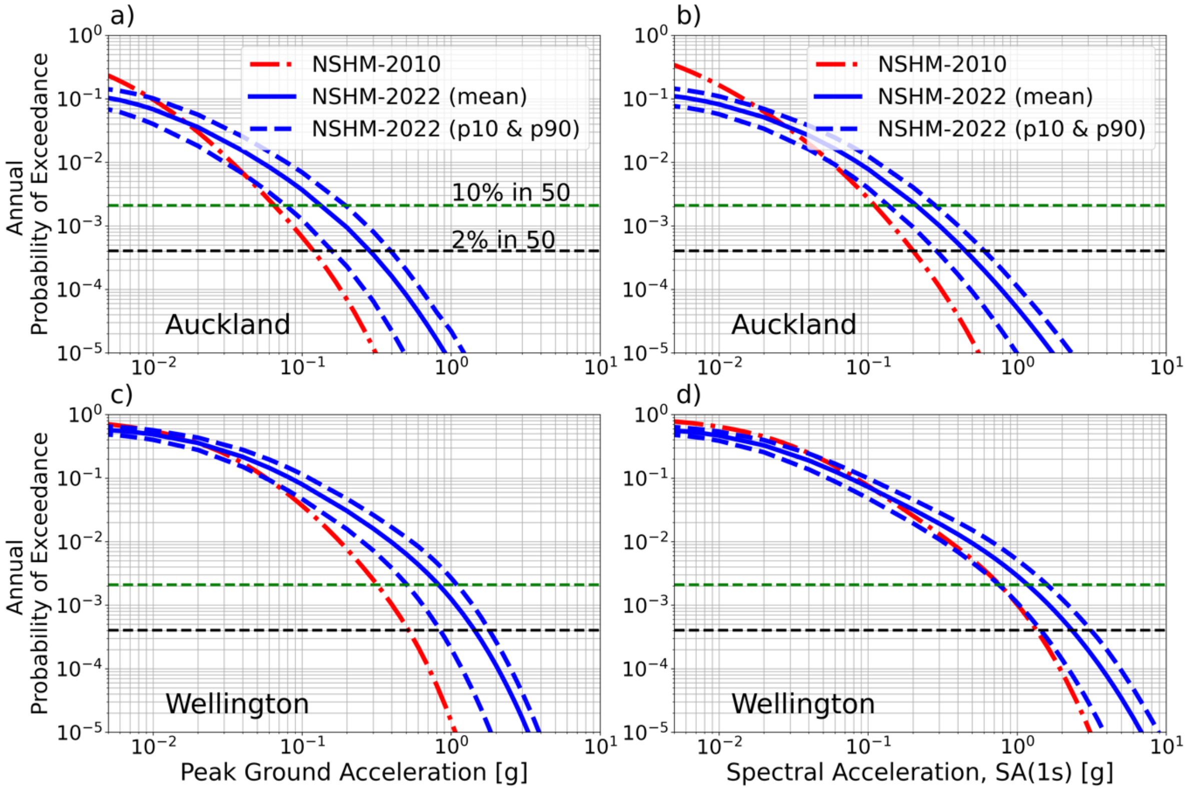


*Figure 3 Hazard curve comparisons from NZ NSHM 2010 and NZ NSHM 2022 for peak ground acceleration (PGA) and spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

## 4 HAZARD CHANGES DUE TO UPDATE IN GMCM

It is well known that the GMCM is a crucial and consequential component of any seismic hazard model. There are various approaches available in literature to build a GMCM for a particular application. In the context of NZ NSHM 2022, the GMCM adopts a hybrid framework in which a weights on model approach was used along with the inclusion of the NZ-derived backbone GMMs (two for crustal events and one for subduction events) as the branches of the GMCM logic tree. As mentioned earlier, the NZ NSHM 2010 adopts a single GMM for the GMCM component. This results in an obvious and significant difference between the two hazard estimates in that the NZ NSHM 2022 provides a suite of hazard curves which capture the epistemic uncertainty in ground-shaking forecasts at a given location.

In this section, we demonstrate the impact of updating the GMCM, that is, the impact of GMCM-2022 vs. GMCM-2010. For that purpose, the GMCM-2010 is replaced by GMCM-2022 while keeping the SRM-2010 as the source characterization model. The hazard results obtained in this way are compared with those from NZ NSHM 2010. Figure 4 shows the comparison of hazard curves for PGA and SA (1s) at a site in Auckland and Wellington with a $V_{S30}$ = 250 m/s. Figure 5 shows the comparison in terms of hazard ratio maps for PGA and SA (1s) for 10% and 2% PoE in 50 years. Note that for hazard ratio maps, the hazard is computed on a grid of points (0.2º×0.2º) by assuming a constant $V_{S30}$ = 250 m/s at each grid point.

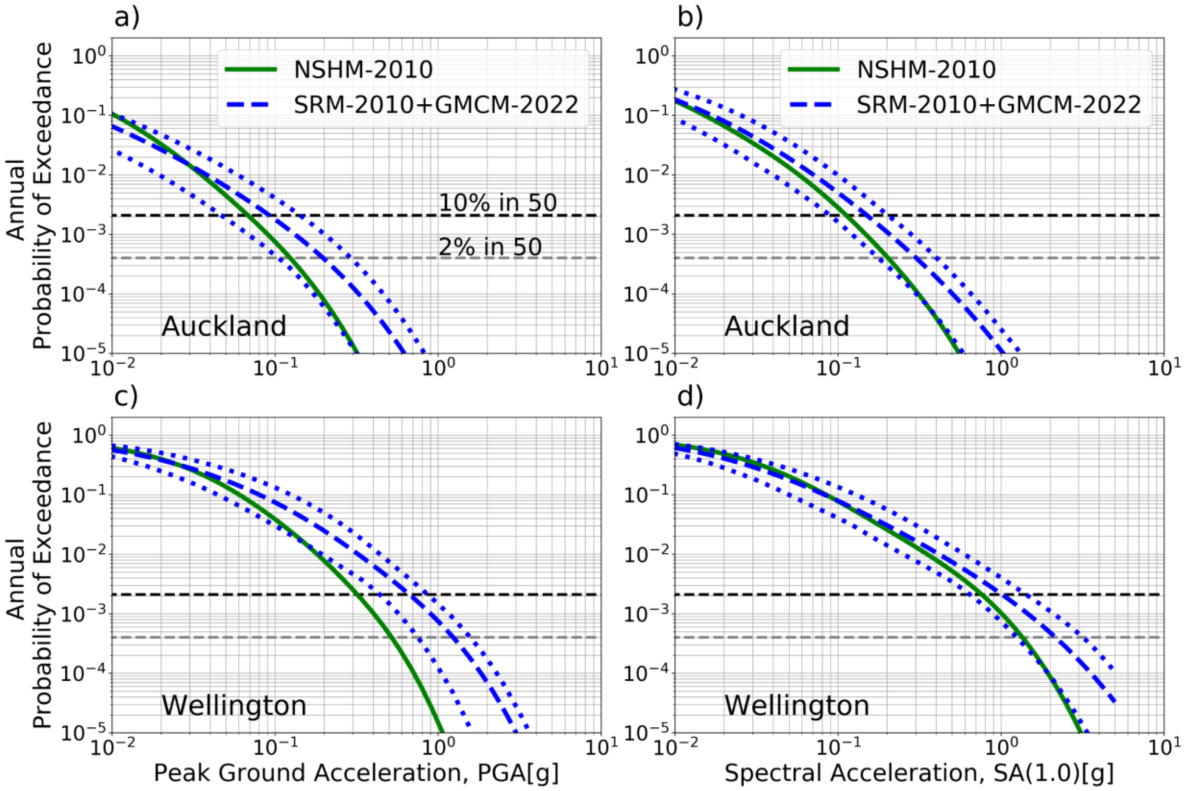


*Figure 4 Hazard curve comparisons showing the impact of update in GMCM for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

It is clear from Figures 4 and 5 that just updating the GMCM-2010 by GMCM-2022 results in a significant change in hazard mainly in the high hazard regions such as the eastern margin of the North Island and south-western portion of the South Island. Also, the impact on the hazard is stronger for PGA than that for SA (1s). In fact, in a relatively low hazard region such as Auckland the increase in hazard for 10% of PoE in 50 years is significant and is almost a factor of two increase for 2% PoE in 50 years. A stronger impact for lower probability ground-motion (e.g., 2% in 50 years) is mainly due to stronger impact of the aleatory uncertainty. For further details on the impact of updating GMMs for individual tectonic types the reader is referred to Bora et al. (2023). Given that the GMCM -2022 comprises global as well as NZ-adjusted GMMs for both crustal and subduction sources, one would naturally be interested to know the impact of the global GMMs vs. NZ-adjusted GMMs. Figure 6 shows hazard curves with four combinations of GMMs and SRM-2022: 1) only global GMMs used in the GMCM with SRM-2022, 2) only NZ-adjusted GMMs used in the GMCM, 3) only NZ-adjusted backbone GMMs used in the GMCM, and 4) full GMCM-2022. Note that for all the four cases, a uniform weighting scheme is adopted. Bora et al. (2023) have shown that the impact of logic tree branch weights in the GMCM logic tree was limited to 5% difference in hazard over all of NZ. From Figure 6 it can be observed that the impact of GMM choices for a GMCM logic tree is chiefly significant (a factor of two) for high-hazard region such as Wellington both for PGA and SA (1s) with opposite effects. For PGA, the hazard due to global GMMs is larger while for SA (1s) the hazard due to NZ-adjusted GMMs is larger.

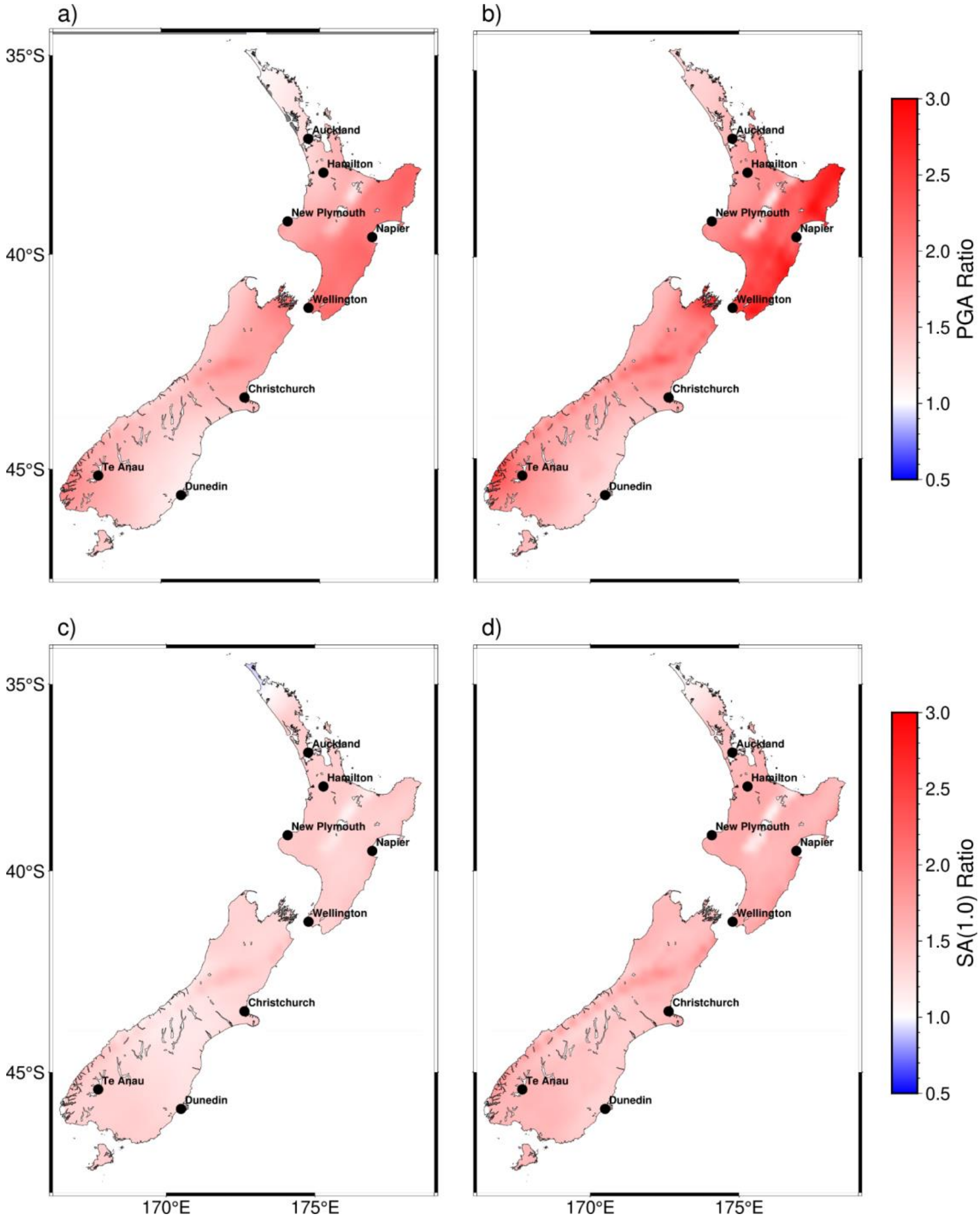


*Figure 5 Hazard ratio maps showing the impact of update in GMCM computed as SRM-2010 + GMCM-2022/NZ NSHM 2010 for peak ground acceleration (PGA) and spectral acceleration, SA(1s) corresponding to 10% probability of exceedance in 50 years (a, c) and 2% in 50 years (b, d) assuming a constant $V_{S30}$ = 250 m/s at all grid points.*

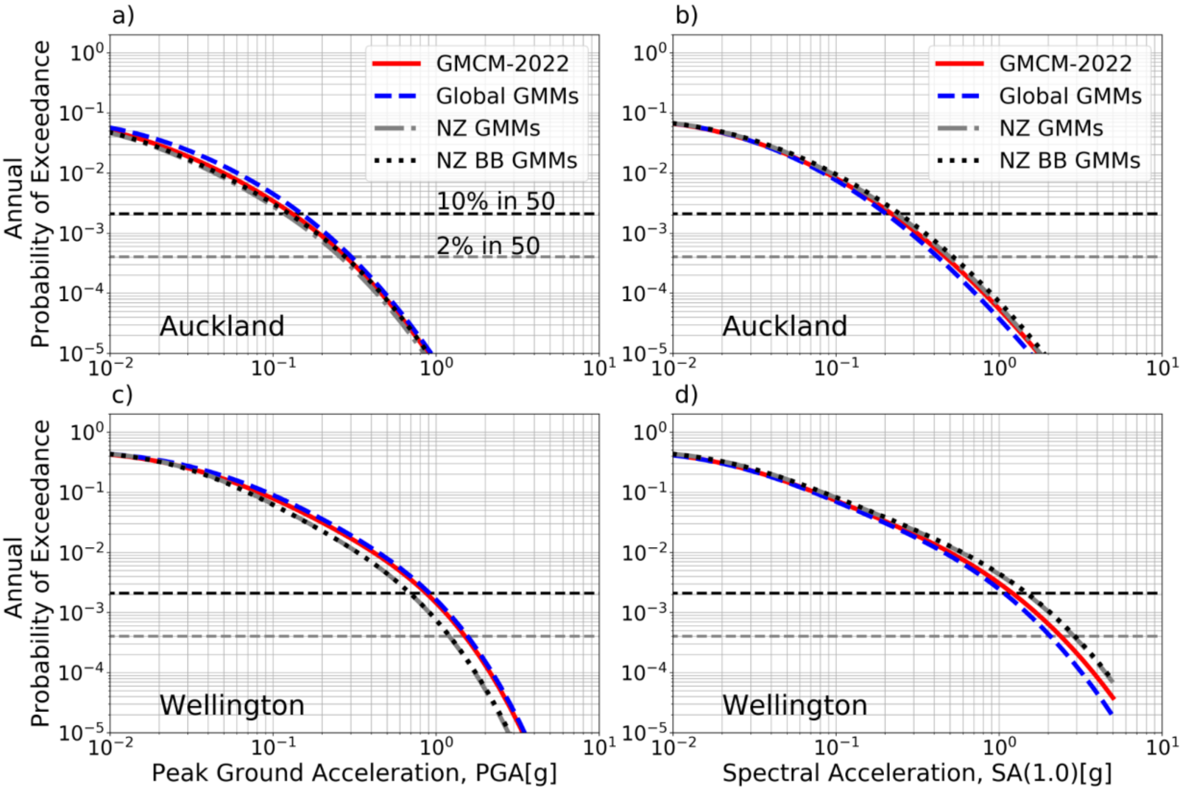


*Figure 6 Hazard curve comparisons showing the impact of the choice of ground-motion models (GMMs) for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

## 5 HAZARD CHANGES DUE TO UPDATE IN SRM

Having seen the significant impact of GMCM updates from GMCM-2010 to GMCM-2022, in this section we evaluate the impact of the updates made in the source characterization models, that is, from SRM-2010 to SRM-2022. For that purpose, hazard was computed with two combinations of SRMs and a GMCM as : 1) SRM-2010 and GMCM-2022, and 2) SRM-2022 and GMCM-2022. Note that for the latter case, a single and highest weighted branch is used from the full SRM-2022 logic tree. One may also note that for both the cases the full GMCM-2022 logic tree is kept common. Figure 7 shows the hazard curve comparisons for the two cases for PGA and SA (1s) at a site in Auckland and Wellington with $V_{S30}$ = 250 m/s. Figure 8 shows the hazard ratio maps (similar to Figure 5) for PGA and SA (1s) corresponding to 10% in 2% PoEs in 50 years. It is evident from Figure 7 that in low-hazard regions such as Auckland the impact of updating SRM-2010 to SRM-2022 is stronger than that of updating GMCM-2010 to GMCM-2022. In high-hazard regions such as Wellington, the impact of updating SRM-2010 to SRM-2022 is lower than that of updating GMCM-2010 to GMCM-2022. As one can observe from Figure 8, indeed this is the case that along the eastern margin of the North Island the impact of SRM update is rather small in comparison to the GMCM update (Figure 5) while at the same time in north-western portion of the North Island (i.e., Northland) and south-eastern portion of the South Island the impact of SRM update is larger.

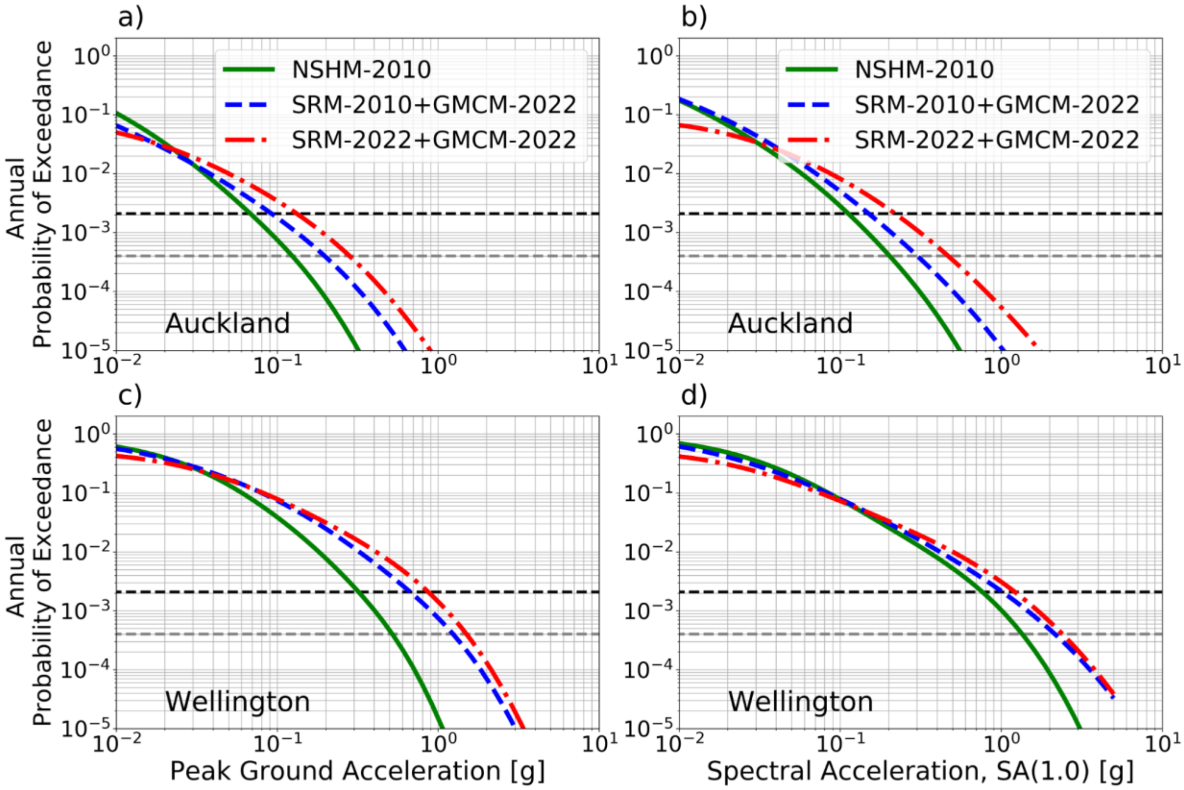


*Figure 7 Hazard curve comparisons showing the impact of update in the SRM for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

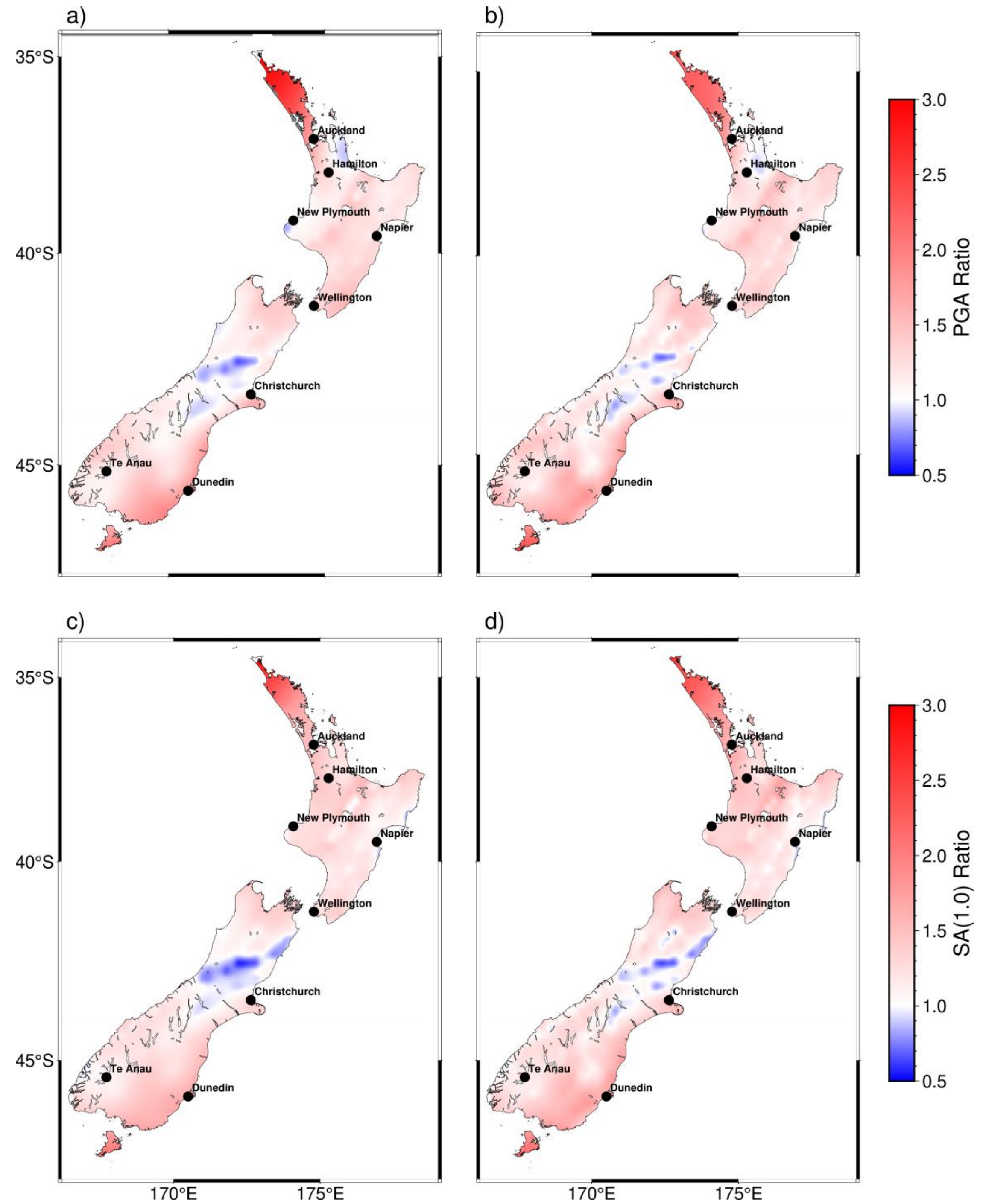


*Figure 8 Hazard ratio maps showing the impact of update in SRM computed as (SRM-2022+GMCM-2022)/(SRM-2010+GMCM-2022) for peak ground acceleration (PGA) and spectral acceleration, SA(1s) corresponding to 10% probability of exceedance in 50 years (a, c) and 2% in 50 years (b, d) assuming a constant* $V_{S30}$ *= 250 m/s at all grid points.*

## 5.1 Hazard changes due to update in individual source types

In this subsection, we further dissect the changes in hazard that are driven by the updates in SRM-2022 in terms of contributions that are coming from crustal sources vs. subduction interface sources. For that purpose, hazard is computed in four additional combinations of SRM and GMCM: 1) SRM-2010 with only crustal source and GMCM-2022, 2) SRM-2022 with only crustal sources and GMCM-2022, 3) SRM-2010 with only interface sources and GMCM-2022, and 4) SRM-2022 with only interface sources and GMCM-2022. As mentioned earlier, a single highest weighted branch is used from SRM-2022. Figure 9 shows the hazard curve comparisons for PGA and SA (1s) at a site in Auckland and Wellington with $V_{S30}$ = 250 m/s. For comparison the hazard curves from SRM-2022 (all sources) and GMCM-2022 are also shown. Clearly, such comparison plots also show the impact of the dominant tectonics. For example in Auckland the relative impact of the updates (from SRM-2010 to SRM-2022) is stronger for interface sources although they are not dominant contributors to hazard in Auckland both for PGA and SA (1s). In Wellington, for PGA the subduction interface sources are dominant while for SA (1s) both crustal and subduction interface sources are dominant contributors mainly towards lower probability ground-motions. Interestingly, for Wellington, while the update in interface sources (from SRM-2010 to SRM-2022) results in increase of hazard, the update in crustal sources results in lowering of hazard for both PGA and SA (1s).

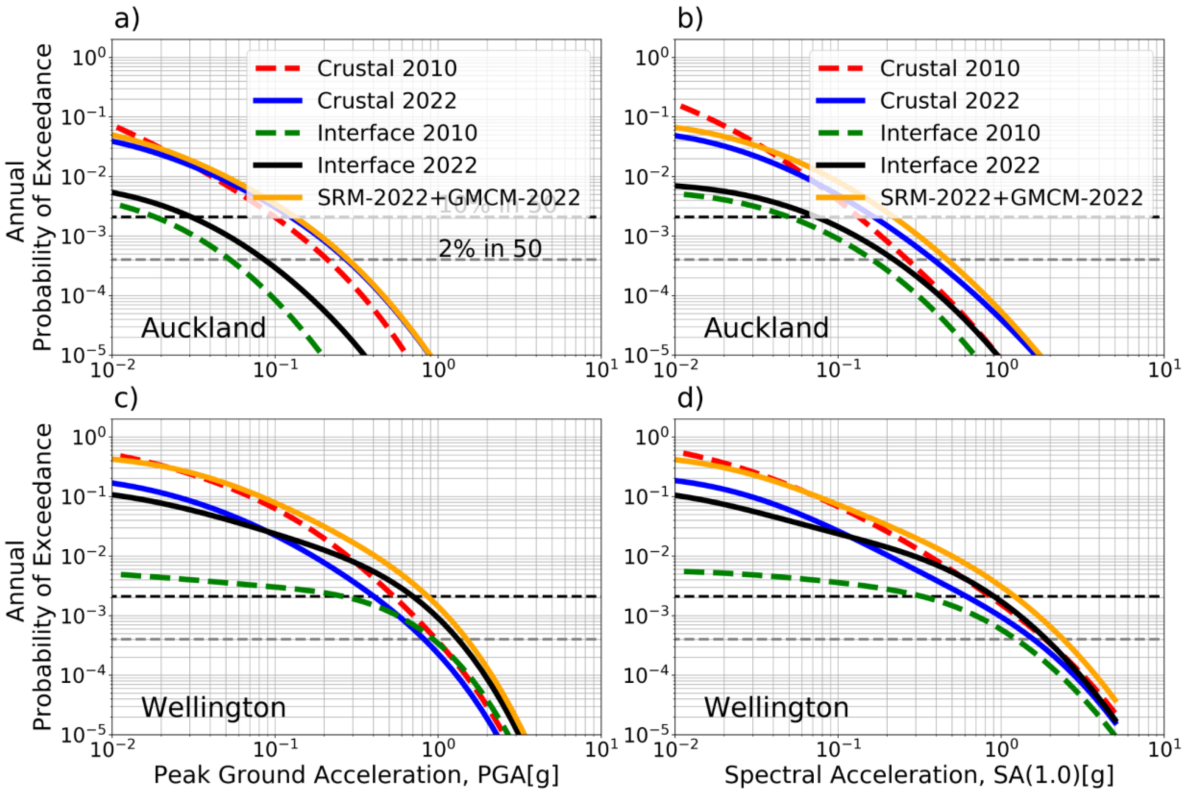


*Figure 9 Hazard curve comparisons showing the impact of update in SRM (individually for each source type) for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

## 5.2 Hazard changes due to modelling of fault sources

As noted earlier, a major shift with regard to the source characterization modelling in NZ NSHM 2022 was in the modelling paradigm of the fault sources for potential earthquake ruptures. The SRM-2022 employs an IFM to model the occurrence rates of multiple and potentially connected ruptures on upper-plate faults and subduction interfaces separately, while SRM-2010 typically adopted a "characteristics" single-magnitude estimate for each specified active fault earthquake source. It is worth noting that connectivity of upper-plate fault ruptures with subduction interface ruptures was not considered in NZ NSHM 2022 (not was it in NZ NSHM 2010).

Thus, in this subsection we illustrate the impact on hazard resulting from the philosophically divergent views of modelling active fault earthquake sources in the "segmented" NZ NSHM 2010 compared to the "non-segmented" NZ NSHM 2022. Figures 10 and 11 show hazard curves for PGA and SA (1s) obtained from the crustal fault sources and subduction interface fault source, respectively, at Auckland and Wellington. The hazard curves from the SRM-2022 (highest weighted branch) are also shown for comparison. Note that in all the three cases GMCM-2022 is employed with $V_{S30}$ = 250 m/s at both the locations. Clearly, in Auckland neither crustal and interface fault sources are the dominant contributors to hazard. In Auckland, most of the hazard is derived from the DSM. In Wellington, however, fault sources are dominant contributors particularly towards lower probability ground-motions. Figure 10 shows that in Wellington the update in modelling of crustal faults from SRM-2010 to SRM-2022 results in lower hazard mainly for ground-motions corresponding to 10% PoE in 50 years and for higher probabilities. The impact of update in modelling of the interface fault sources results in significant increase in hazard in Wellington for both 10% and 2% PoE in 50 years. One may also observe that interface fault sources are the dominant source of hazard for Wellington towards low probability ground-motions. Clearly, the differences observed in hazard (Figures 10 and 11) are mainly due to the differences in magnitude frequency distributions and the geometries of the potential ruptures.

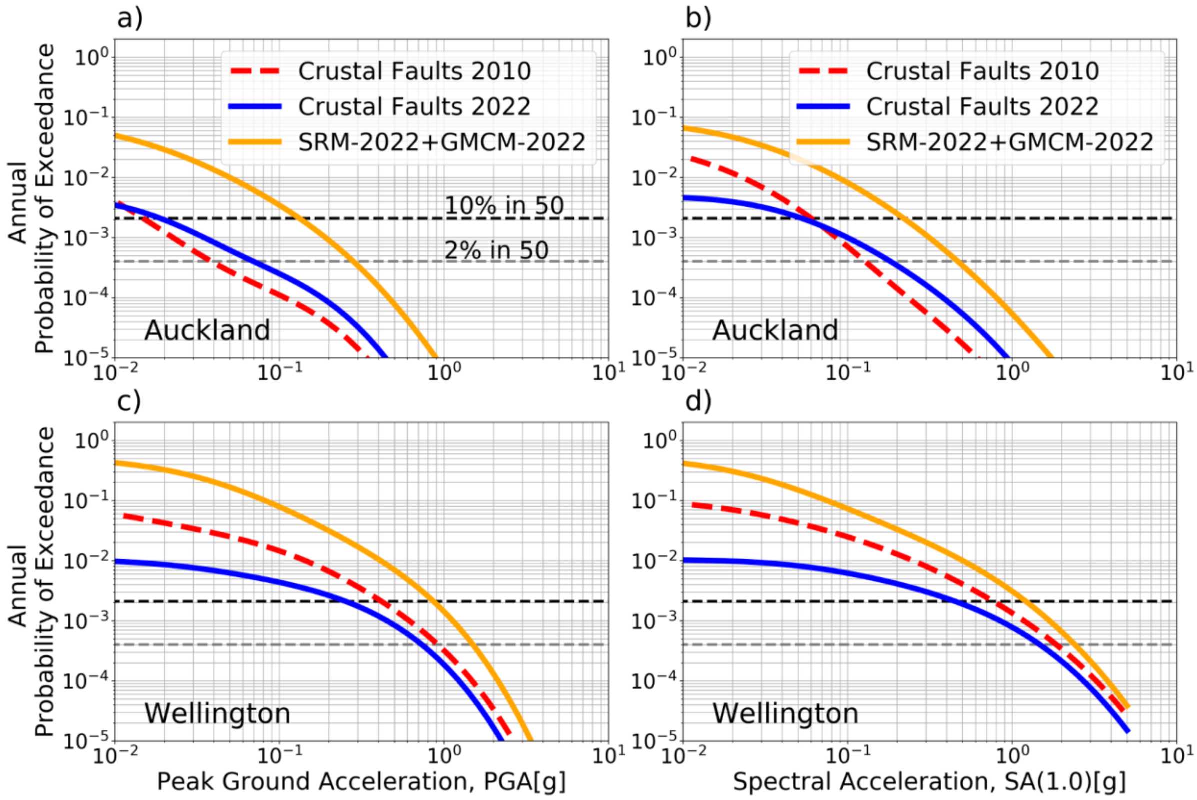


*Figure 10 Hazard curve comparisons showing the impact of update in modelling of crustal fault sources for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

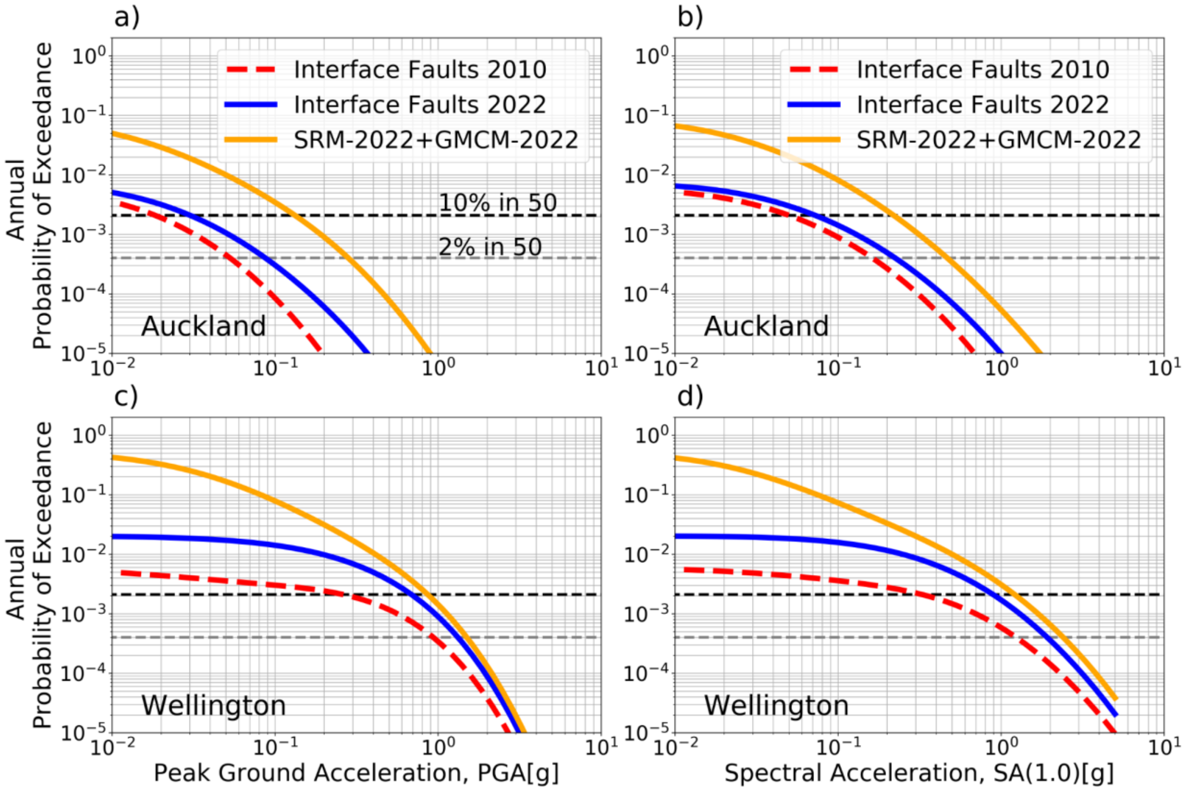


*Figure 11 Hazard curve comparison showing the impact of update in modelling of interface fault sources for peak ground acceleration (PGA), spectral acceleration, SA(1s) at a site in Auckland (a, b) and Wellington (c, d) with $V_{S30}$ = 250 m/s.*

## 6 CONCLUSIONS

The NZ NSHM 2022 presented significant changes in hazard results compared to NZ NSHM 2010. These changes encompass substantial revisions across various components of the hazard model. This study dissects these changes into the components that are originating from updates in the SRMs and GMCMs separately. The update in the GMCM (GMCM-2010 to GMCM-2022) is a dominant driver of hazard increase overall across the entire country with large impacts in high-hazard regions such as along the eastern margin of the North Island and the south-western portion of the South Island. The update in SRM (from SRM-2010 to SRM-2022) also results in overall increase in hazard with dominant effects in low-hazard regions of north-western portion of the North Island and south-eastern part of the South Island. Further dissecting the changes indicated significant differences in hazard results due to modelling of the fault sources between NZ NSHM 2010 and NZ NSHM 2022. The NZ NSHM 2022 update in modelling the subduction interfaces in general increases the hazard. The impact of update in modelling of crustal faults resulted in lowering of hazard in Wellington while in Auckland it resulted in increased hazard although not being a dominant contributor to hazard. It is also worth mentioning that the NZ NSHM 2022 utilizes $V_{S30}$ as a proxy for the local site-effects as opposed to a subsoil site class used in NZ NSHM 2010.

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