Using hazard curves to examine the sampling of epistemic uncertainty across the Australian continent

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Abstract

The Seismic Source Model (SSM) for the draft 2018 National Seismic Hazard Assessment (NSHA18) contains ten spatial source zones, five of which have been combined with a fault model. The resulting 14 seismic source models (SSM) are the most ever used for any national scale PSHA. This provides a unique opportunity to study how these source models, produced by 10 different teams, sample the epistemic uncertainty. It involves comparing the suite of hazard curves; if the hazard curves are all subparallel then they are not effectively sampling uncertainty as they could be replaced by a single mean model. In the paper I use this approach to examine the epistemic uncertainty for 24 sites (8 capitals, 10 other cities and 6 indicative sites). I find that epistemic uncertainty has been thoroughly sampled with the range of PGAs predicted by the various models typically varying by a factor of six (e.g. 0.01 – 0.06) to 10. The SSM that gives the highest, lowest and closest to the mean hazard curve varies from site to site with no single model able to consistently replicate the mean hazard. Within the four classes of SSM (smoothed, local, regional and background) there is less variation, suggesting that the total number of models could be reduced without loss in sampling the epistemic uncertainty.

Keywords: seismic hazard, probabilistic seismic hazard assessment, epistemic uncertainty

Introduction

The Seismic Source Model (SSM) for the 2018 National Seismic Hazard Assessment (NSHA18) contains 10 spatial source zones, four of which have been combined with a fault model as well as two smoothed seismicity models. The resulting ~15+ source models are the most ever used for any national scale probabilistic seismic hazard analysis (PSHA).

Leonard discussed the requirements for accurate magnitude frequency distribution (MFD) estimation (i.e. *a* requires 25+ and *b* requires 400+ earthquakes) and how this might best be achieved for various scales of seismic zonation models. Leonard (2016) noted that seismic source models (SSMs) for a national seismic hazard model (NSHM) are attempting to provide the best estimate of the distribution of earthquakes over the next 50 years and discussed the assumptions implicit for various classes of seismic source models. For smoothed seismicity models the key assumption is that the catalogue, which for most of Australia is comprehensive for at most 50 years, captures all the variation in the spatial distribution of seismicity; that is the seismicity is highly stationary on a time scale of 50 years. For spatial source zones the key assumptions are that the seismicity is spread uniformly within a source zone and the method used to define the zones (typically some combination of the known seismicity, geological features, geophysical features and active faults) captures the expected spatial variation in the distribution of earthquakes for the next 50 years. There is a trade-off between the size of the source zone and an accurate estimate of the MFD, with fixed regional *b* and *a* varying at a finer scale being one approach for a SSM with many small zones.

The large number of SSMs provides a unique opportunity to study how these source models, produced by 10 different teams, sample the epistemic uncertainty. Except for SSMs with large zones, typically called background SSMs, the hazard at most sites is the sum of the contributions from multiple sources at varying distances. As such comparing MFDs between models is not meaningful. Typically de-aggregation is used to understand the contribution of earthquakes of various magnitudes and distances, but, due to the 3D nature of the information, this method does not lend itself to direct comparisons of multiple SSMs. Leonard (2017) suggested using the hazard curve, which probabilistically captures the complete spatial and magnitude distribution of earthquakes, to compare models. He proposed that the variation in the hazard curves for a single site is a possible measure of the degree of success at capturing the epistemic uncertainty in the SSM of that site. This paper extends the method proposed by Leonard (2017) to investigate the sampling of epistemic uncertainty of SSMs for 24 sites across Australia. I note that most of the SSM are immature, having not yet been tested or widely used, so may be overestimating the uncertainty.

Method

Leonard (2017) proposed a method for examining how well multiple models sample the uncertainty in a PSHA. The method suggests that a suite of hazard curves that are parallel or subparallel do not effectively sample epistemic uncertainty as the upper and lower hazard curves cancel each other out and the mean hazard could be reproduced by a single model. Leonard (2017) suggests that to effectively sample uncertainty, models should be fundamentally different and that one measure of the difference in alternative models is that their hazard curves be different. The hazard curves for different GMPEs are generally not parallel and cross each other so that the relative position of the GMPEs varies with the Probability of Exceedance (PoE). This is reflecting that close to an earthquake one GMPE will give a higher ground motion than another but at larger distances this might reverse. Ground motion versus magnitude, at a fixed distance, also has this property. Almost any suite of GMPEs will have this behaviour, including those produced using identical data sets, such as the NGA-West models (Abrahamson et al. 2008) or the NGA-West2 models (Bozorgnia et al. 2014). This is the fundamental basis of including multiple GMPEs in any PSHA. Similarly I propose the comparison of hazard curves as a method for investigating the sampling of epistemic uncertainties by multiple seismic source models.

Table 1 The SSMs tested, W is the weighting of the SSM.

Code	***W***	***SSM***	***Code***	***W***	***SSM***
AUS6	0.018 0.086	Dimas et a. 2016	CM12	0.061	Clark & McPherson
DV16	0.019 0.109	Dimas & Venkatesan 2016	ARUP-B	0.034	Mote
GA13-R	0.025	Leonard et al. 2013	SM16	0.013	Sinadinovski & McCue 2016

	0.205				
L08	0.035	Leonard 2008	GA13-B	0.024	Leonard et al. 2013
ARUP-R	0.034	Mote	Smooth	0.088 0.249	Griffin/Cuthbertson 2016

Note AUS6, DV16, GA13-R and Smooth have both source zone only and source zone plus fault model versions, in all cases the higher weight is the source plus fault SSM.

The SSMs have been divided into three classes. The Background SSM have fewer than five large source zones, the Regional SSM have 5 – 10 zones and the local SSM have more than 20 zones. Each of these three classes have made a different choice between the scale for areas of uniform spatial distribution and so the scale for variation in the spatial distribution of seismicity. The Background SSMs, in effect, assume that the distribution of small (e.g. Mw<4.5) earthquakes over the last 50 years is a poor predictor of the large (i.e. Mw>5.5) earthquakes in the next 50 years; that is seismicity is not spatially stationary. The Regional SSM assume that the distribution of small earthquakes over the last 50 years is a good predictor of the large (i.e. Mw>5.5) earthquakes in the next 50 years at the scale of several hundreds of kilometres but not at the scale of 10s of kilometres. The local SSM assumes that the distribution of small earthquakes over the last 50 years is a good predictor of the large (i.e. Mw>5.5) earthquakes in the next 50 years at the scale of a few 10s of kilometres. The smoothed seismicity models assumes that the distribution of small earthquakes over the last 50 years is a good predictor of the large (i.e. Mw>5.5) earthquakes in the next 50 years at the scale of approximately 10 km; that is seismicity is very spatially stationary.

The National Cities Performance Framework (NCPF 2017) covers 22 urban centres of Australia, constituting the 21 largest cities plus western Sydney. I used this framework to select the 17 cities. An additional seven locations were selected to provide a diverse coverage of geography and high and low seismicity. As Carnarvon, Onslow, Karratha, Dampier and Port Headland are all in wind loading Region D and buildings must be designed to withstand a Category 5 cyclone (300+ km/hr), they were not included, leaving Broome as the only town in northwest W. A. included in this analysis (Figure 1).

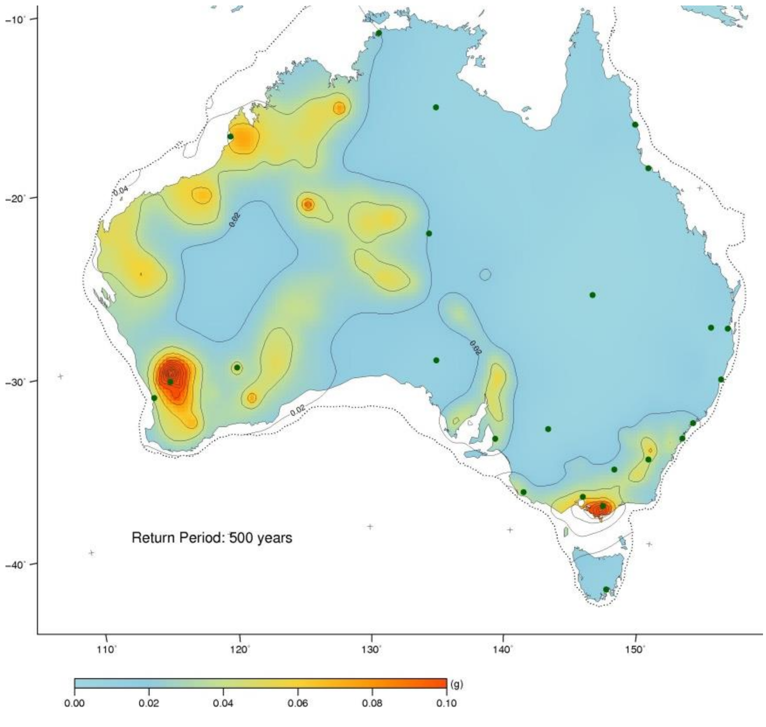

Figure 1 **The 2017 national PSHA, for bedrock, with the 24 sites examined in this study plotted as green circles.**

Results

In the hazard curve figures (Figures 2–4), the four blue curves are the background zones. The purple dashed curves are the Regional SSMs and the orange and red curves are the Local SSMs. For the Local SSMs the SSMs without the fault model are shown as dotted lines. In cities, such as Sydney and Albury, where the local SSMs include an active source zone encompassing the city the background zones have a lower hazard. In cities, such as Quilpie and Kalgoorlie, where the local SSMs do not include an active source zone encompassing the city the background SSMs have the higher hazard.

Where active faults are nearby, such as Adelaide and Canberra (Figure 2), the combined fault and zonation model gives a significantly higher hazard. However, where active faults are not present, such as Sydney (Figure 2), the curves, with and without a fault model, are the same. For Dowerin (midway between Cadoux and Meckering; Figure 4) the many faults identified in the Western Australian Wheatbelt region do not contribute to the hazard; the source zones are so active that the hazard from the relatively slow slip faults is trivial, similarly for Perth (Figure 1). This is consistent with the findings of that the contemporary seismicity rate is about an order of magnitude greater than that required to build the mapped scarps.

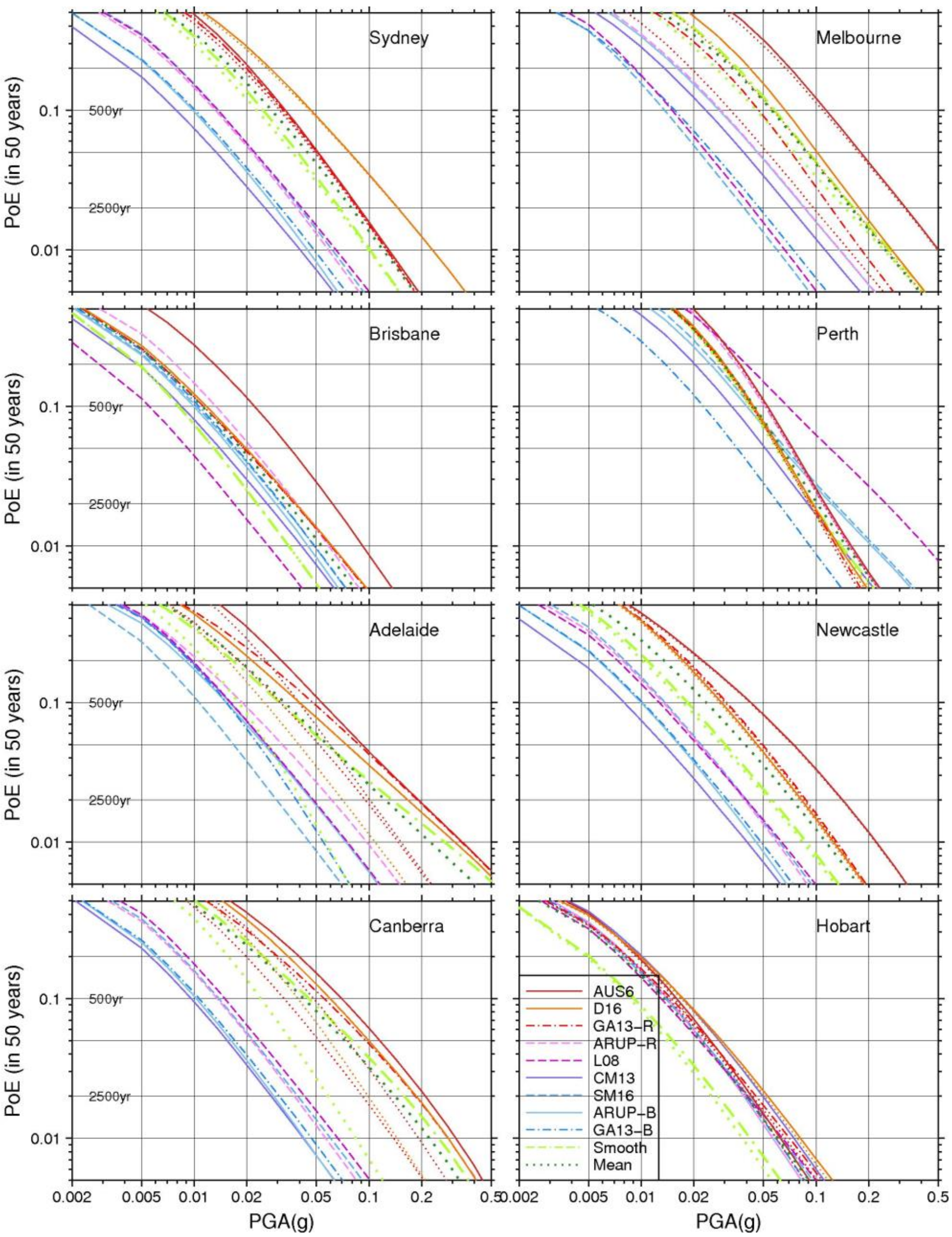

Figure 2 The hazard curves for the Australian capital cities. The AUS6, D16 and GA13-R have two versions: with source zone plus fault model (as per legend) and source zone only (dotted line of matching colour) versions.

The Perth hazard curves have the behaviour that at PoE of less than 5% in 50 years (~1000 years) the local seismic source models give a higher hazard than the background models whereas at lower probabilities (i.e. 2500 years) the background models give a higher hazard. This is because all the local source models have very active zones east of the Darling Fault and very quiet zones encompassing Perth. This results in the seismicity controlling the hazard being at least 25 km from the Perth CBD. The background zones all include Perth in a zone of intermediate activity and that allows for the possibility that earthquakes occur very close to Perth.

Adelaide is the opposite of Perth, with the smaller the PoE the larger the difference between the combined and the background models. The longer the return period the higher the contribution of the active faults to the hazard. This reflects that the Flinders and Mt Lofty Ranges and East Gippsland have the highest density of mapped high slip-rate faults in Australia. For Morwell, in East Gippsland, the faults dominate the hazard. Canberra and Albury are the two other sites where the faults are the major contributor to the hazard.

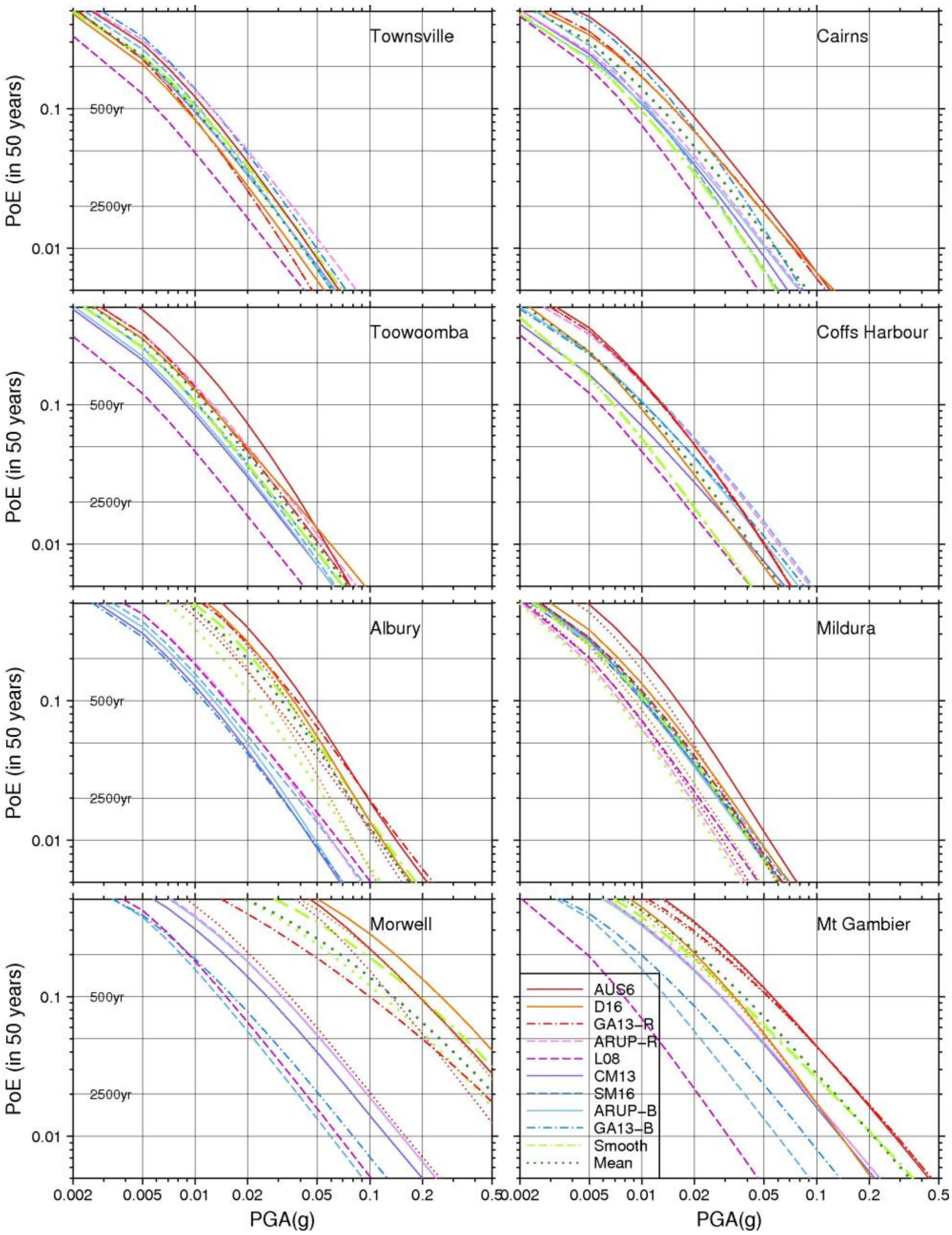

Figure 3 The hazard curves for major Australian towns and cities

For Melbourne, Canberra (Figure 2) and Quilpie (Figure 4) all the hazard curves are sub-parallel and the mean curve does not cut across the suite of curves. For Melbourne the local SSMs are the major contributors to the hazard, whereas in Quilpie the background SSMs are the major contributors. The sub-parallel hazard curves suggest that the various SSMs have similar spatial pattern of earthquakes and the various SSMs are mostly reflecting varying activity rates. This suggests a single SSM (e.g. GA13-R) could replace all the source zones. Hobart is an extreme case with all the curves are very close and so having multiple SSMs is redundant.

The four background models consistently give similar hazards, with the range about their mean typically being a factor of 1.5 (1.3 – 1.7). However their ranking from city-to-city varies with the Domains model most often closest to the mean value. SinMc16 is the most variable of the four background models, tending to fluctuate from the lowest (e.g. Adelaide and Melbourne) to the highest (e.g. Sydney and Perth).

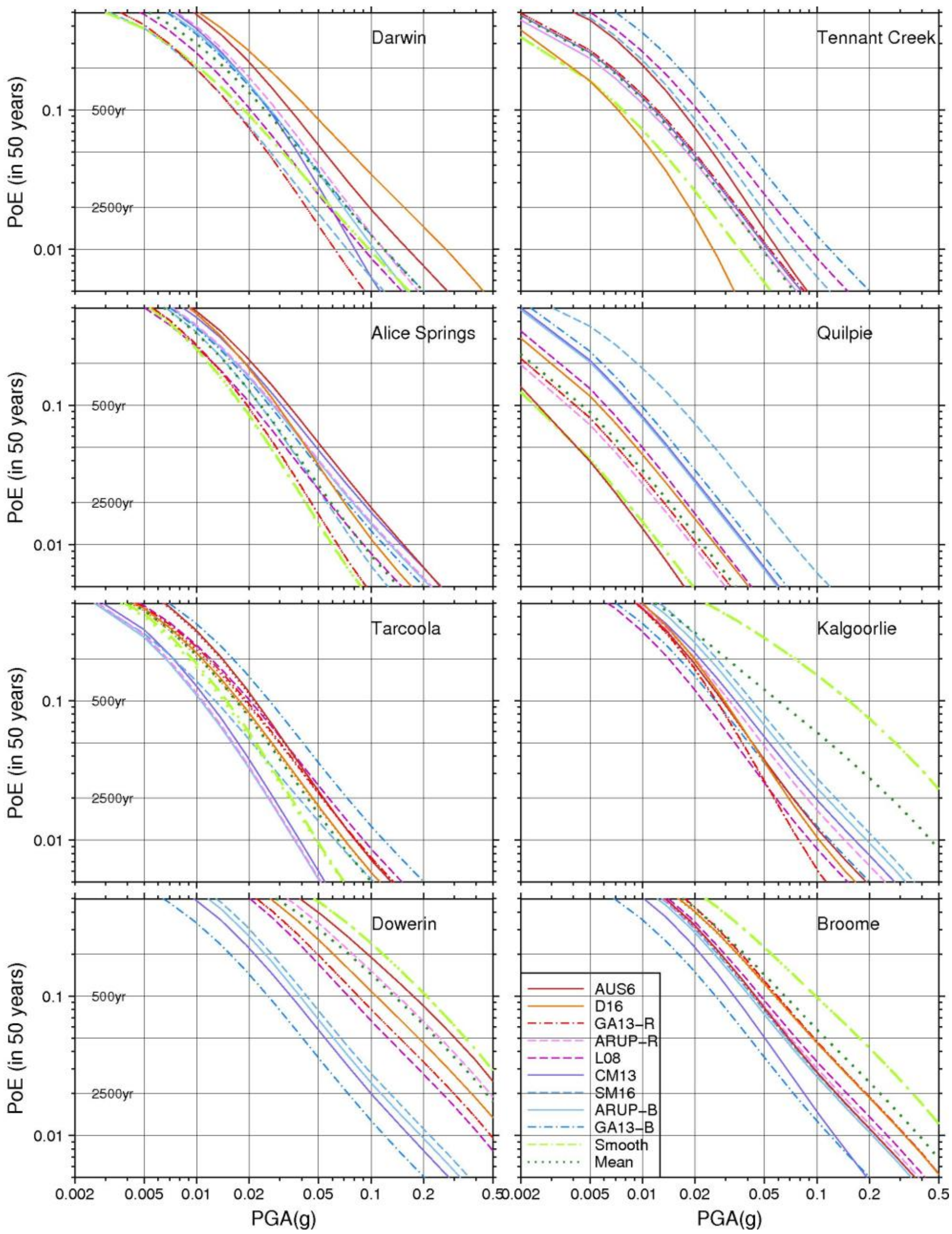

Figure 4 The hazard curves for major Australian towns and cities.

Of the two regional SSMs (i.e. ARUP_Reg and L08) Leonard (2008) is the most variable. It produces very high hazard for Perth (as it ignores the major boundary of the Darling Fault) and produces low hazard for Melbourne (as it spreads the active of East Gippsland over much of SE mainland Australia). This reflects that it was never intended for seismic hazard studies but for regional strain-rate studies. Except for Dowerin, the ARUP_Reg model consistently sits near the four background zones.

The three Local SSMs tend to group together. Of all the SSMs, AUS6 consistently gives the highest hazard, particularly in the more active areas (e.g. Adelaide and Melbourne). Its total hazard across the continent is the largest of the SSMs, with D16 also having higher than average hazard values. The final magnitude frequency distributions (MFD) used in the PSHA used an asymmetrically weighted sum of occurrence rates considering uncertainties for both Gutenberg-Richter *a* and *b*-values. The *b*-values were determined based on the GA13-B model, while *a*-values were determined on a source-by-source basis for each SSM . As AUS5 and D16 have many small source zones the MFD *a*-values were often calculated with relatively few earthquakes and this results in high uncertainty of these variables. So the high overall hazard for AUS6 and D16 is a result of how uncertainty in *a* and *b* was included in the final MFD and not an inherent property of the SSMs.

The Smoothed Seismicity (SS) SSM is typically similar to the three Local SSMs. However, for Hobart the hazard curve is well below those of the other SSMs, which are tightly clustered. For Broome and Kalgoorlie it sits higher than the other hazard curves. In the case for Broome, the SS model might be picking up a clustering of earthquakes, possibly associated with the mb 6.1 1979 earthquake, that does not contribute significantly in any of the Local SSMs. Even with a total weighting of 0.337, the hazard from the SS model is so much higher than other candidate models that it doubles the mean hazard from 0.028 to 0.06g. Given that Kalgoorlie is a major mining area, it raises the question of whether mine blasts or mining triggered events have been included in the earthquake catalogue. That said, there have been three ML 4.5+ earthquakes near Kalgoorlie since 1960 and these govern the hazard from the smoothed seismicity model at this location.

Discussion

We can say with some confidence that the 15 candidate SSMs have comprehensively sampled the epistemic uncertainty of the spatial distribution of earthquakes. The pattern of hazard curves is different for each of the 24 sites considered herein. Even for sites with very similar hazard and a similar range of hazard curves, the distribution of hazard curves can be very different, for example the SSM giving the highest hazard in Townsville gives the lowest in Mildura. Even sites that are relatively close and that have similar mean hazard levels, such as Cairns and Townsville, may have different patterns of hazard curves. For cities with different seismicity and tectonics, such as Sydney, Adelaide and Perth, as one might expect, the shape and distribution of the hazard curves are different, as is the relative level of the hazard.

For the vast majority of the sites, the hazard curves of the four background SSMs are clustered together, though there are a few exceptions (e.g. Tarcoola). This suggests that the four background SSMs, which had a total weighting of only 0.13, could have been replaced by just one. I would choose the ARUP background SSM, but given the low weighting the choice would not significantly affect the hazard – at least for the 24 sites investigated in this study.

For the chosen sites, the hazard curves of the three local source models also cluster. Given their total weight is 0.46 and the large uncertainties on estimation of *a*-values for zones with few earthquakes, it is difficult to comment on their relative behaviour (e.g. high overall hazard of AUS6 and to a lesser extent D16) or merits. The requirement for significant numbers of earthquakes to be included for accurate MFD estimation has been long recognised (Aki 1965; Weichert 1980; Bender 1983; Tinti and Mulargia 1987). For the MFD to be accurate enough that it does not introduce noise into the SSM, Leonard (2016, 2017) suggests 400, preferably 800, events are required for the estimation of *b* and 25, preferably 100, for *a*. None of the source zones in AUS6, D16 and GA13-R have 400 earthquakes, with perhaps only 10% having 100 earthquakes. This suggests that the approach of regional *b* combined with source zone specific *a*, as applied for the NSHA18, is required for these three SSMs.

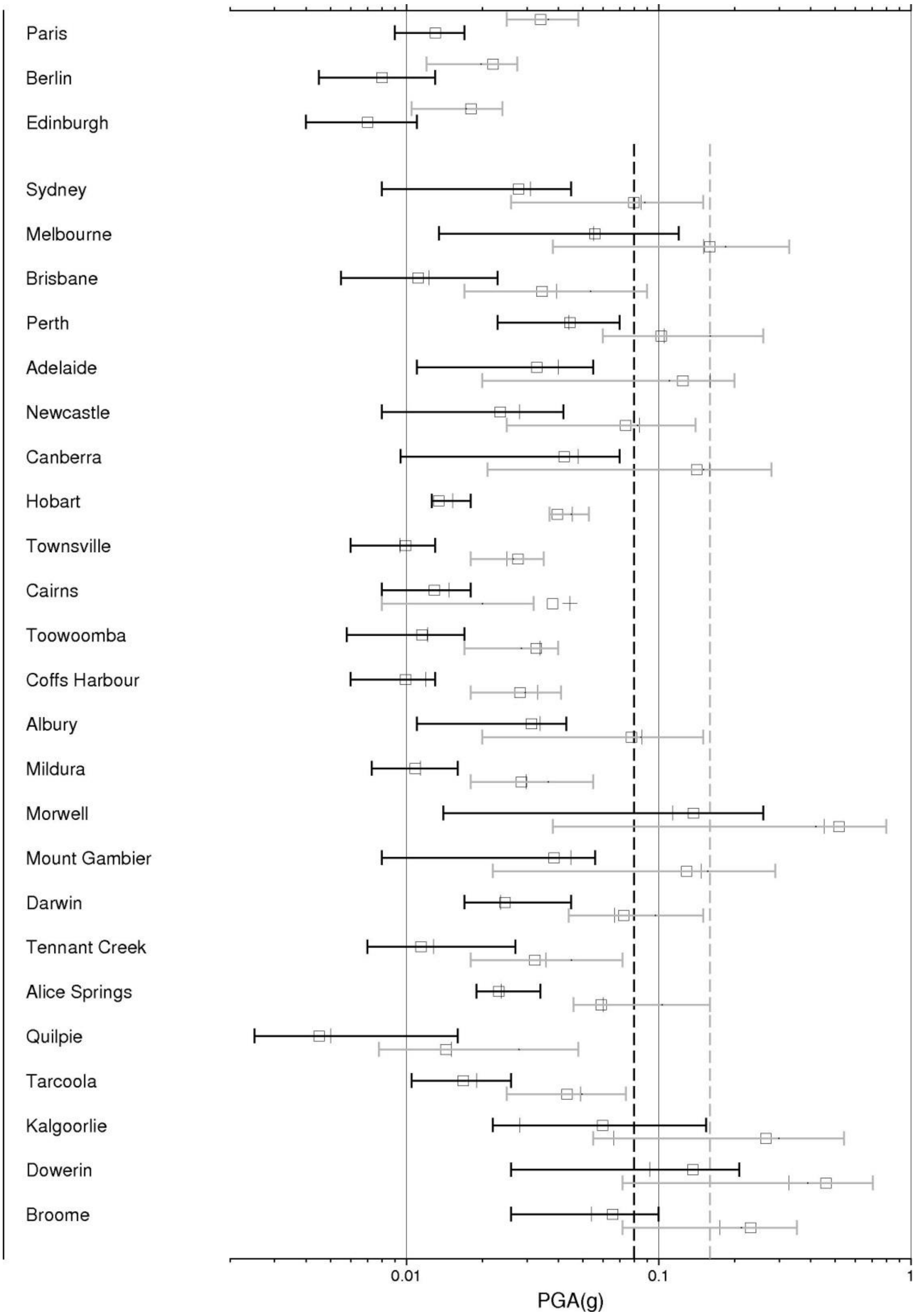

Figure 5 Comparison of range of PGAs for the 14 seismic source models used in this study (475 [black] and 2475 grey]). The results for the three European cities are from Douglas et al. (2014). The vertical dashed lines are the hazard floors proposed for the 2018 update of AS1170.4.

Figure 5 shows the mean and the range of seismic hazard values for each of the 14 SSMs at the 10% and 2% probability of exceedance for the 24 sites studied. Those sites with a wide variation in hazard (e.g. Melbourne, Morwell, Dowerin) tend to be near active source zones. Consequently, the local SSMs give high hazard but the background SSMs return a low hazard. Where there is no local active source zone (e.g. Hobart, Mildura, Alice Springs) the differences in the local and background models is less, so the range narrower. For comparison the seismic hazard values for Paris, Berlin and Edinburgh are shown. Their range is the 15^{th} and 85^{th} percentile hazard, for multiple range of GMPEs and two alternative SSMs used in the SHACC Level 4 SHARE project (Giardini et al.2014). The Australian cities generally have significantly higher hazard than the European cities in analogous tectonic environments, with Brisbane, Toowoomba, Cairns and Mildura being the only cities with hazard comparable to Paris. Townsville is similar to Berlin, with only Quilpie, which was specifically chosen as it has the lowest hazard in Australia, being comparable to Edinburgh. There is no obvious tectonic reason why the hazard around Australian cities should be higher than around comparable European cities.

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