The 11th Canadian Conference on Earthquake Engineering
Canadian Association for Earthquake Engineering

ASSESSMENT OF GROUND MOTION MODELS FOR USE IN SOUTHWEST BRITISH COLUMBIA

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ABSTRACT: Southwest British Columbia (SWBC) is home to a complex tectonic regime that hosts frequent earthquakes. Natural Resources Canada is mandated to develop National Seismic Hazard Models, which underpin the seismic provisions of the National Building Code of Canada. The production of these models requires assumptions on the use of Ground Motion Models (GMMs), often with little empirical evidence to guide the selection of appropriate GMMs. The high seismic risk in SWBC warrants a regular validation of recorded ground-motions to those predicted by the GMMs that are currently used in seismic hazard assessments for this region, as well as those GMMs developed for global tectonic analogues. For earthquakes occurring in SWBC between 1996 and 2015 with moment magnitude $M_W \geq 5.0$, ground-motion data from the Canadian National Seismic Network and the BC Ministry of Transportation and Infrastructure Internet Accelerometer network were extracted for analysis. Pseudo spectral accelerations at 5% damping are calculated, binned (by distance and magnitude) and quantitatively compared to a number of modern GMMs to assess the suitability of each model for evaluating seismic hazard in SWBC. For the shallow, offshore earthquakes assessed in this study, ground-motions are generally overestimated. The offshore and crustal GMMs of Atkinson and Adams (2013) implemented in Canada's most recent seismic hazard model, appear to be more suitable for larger events (M_W 6+) occurring in the North American continental crust.

1. Introduction

Southwest British Columbia (SWBC) – the area extending from offshore Vancouver Island to Hope, BC and from the Canada/USA border to the northern extent of Vancouver Island – is one of Canada's most seismically active regions (Fig.1). The seismicity in this area is a consequence of the relative motion between the Pacific (PA), Juan de Fuca (JdF), Explorer (Ex) and North American (NA) tectonic plates (Ristau et al., 2007). On an annual basis thousands of earthquakes are located in this region. These earthquakes provide us with useful information that can be used to guide inputs to the National Seismic Hazard Model of Canada.

Beginning in 1953 Natural Resources Canada (NRCan) has regularly produced National Seismic Hazard Models of Canada (Adams, 2011). These models underpin the seismic provisions of the National Building Code of Canada (NBCC; Adams and Halchuk, 2003) and are intended for use in city planning and emergency operations. Modern seismic hazard models are based on: observed historical seismicity that can yield magnitude-frequency relationships; GPS slip rates and paleoseismic observations that provide recurrence information for active faults, and; appropriate Ground Motion Models (GMMs) which can be developed from recorded ground-motions of earthquakes (Bozorgnia *et al.*, 2014). As ground-motion databases grow, particularly through technological advances that reduce the cost of data collection, developments in ground-motion modelling progress. These advances have resulted in numerous GMMs being published (Douglas, 2014); each influenced by the ground-motion database they were derived from. An updated suite of GMMs (Atkinson, 2012; Atkinson and Adams, 2013) were implemented in the Fifth Generation National Seismic Hazard Model of Canada (Adams *et al.*, 2015). The Atkinson and Adams (2013) GMMs use a central backbone approach with an upper and lower model to account for the epistemic uncertainty in ground-motion. The suite of models has been developed for several tectonic environments: western active crust, stable continental crust, subduction interface, subduction inslab and oceanic crustal. These updated GMMs represent a significant advance relative to GMMs used in previous editions of the national hazard model.

A large database of SWBC ground-motions have been assembled to evaluate the appropriateness of GMMs used for the 2015 National Seismic Hazard Model of Canada. This work builds on previous work that examines the characteristics of ground-motion attenuation in the SWBC region (e.g., Ristau *et al.*, 2003; Atkinson, 2005; Ristau *et al.*, 2005). A large portion of seismicity in SWBC occurs within the JdF and Ex oceanic plates, not in the NA plate. This introduces an extra layer of complexity for the assessing the appropriateness of GMMs, as the source, path and site are likely to be located in different tectonic plates, which current GMMs often do not take into account.

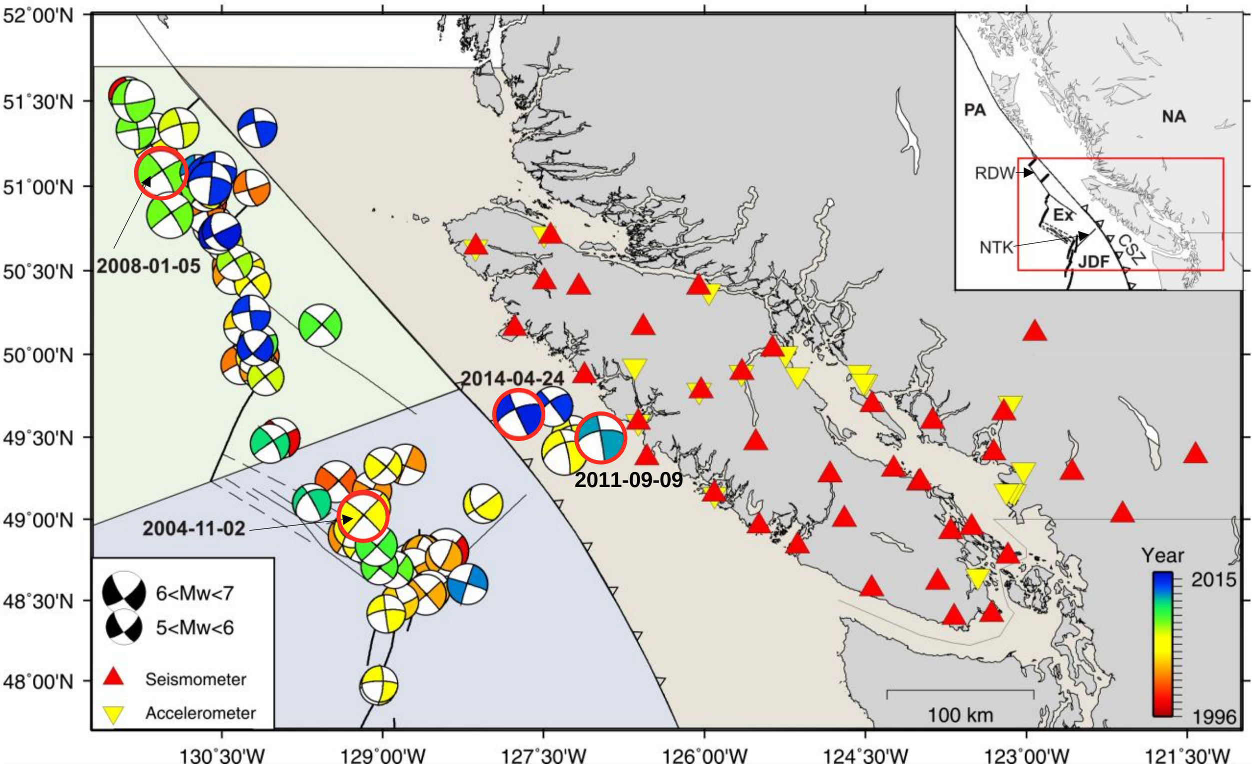

Figure 1 - Tectonic setting of Southwestern British Columbia (SWBC). Beachballs are colored by time occurrence and indicate locations of earthquakes of $M_W \geq 5.0$ from 1996 through 2015, with moment tensor solutions used in this assessment. Filled triangles represent the location of strong- and weak-motion stations included in this study. Shaded areas are the three areas of seismicity in SWBC. Moment tensors outlined in red correspond to discussions in text. CSZ=Cascadia Subduction Zone, Ex=Explorer plate, JdF=Juan de Fuca plate, NA=North American plate, PA=Pacific plate, RDW=Revere-Delwood-Wilson Fault, NTK=Nootka Fault Zone.

For 86 M_W≥5.0 earthquakes that occurred in SWBC between 1996 and 2015 (Fig. 1), miniseed data was downloaded from weak-motion instruments of the Canadian National Seismograph Network (CNSN). In addition, strong-motion data for two larger events recorded on the BC Ministry of Transportation and Infrastructure Internet Accelerometer (IA) network (Rosenberger *et al.*, 2006) were used in analysis. Earthquake parameters for events were obtained from both CNSN moment tensor solutions (Ristau *et al.*, 2003; Kao *et al.*, 2012) and the Global Centroid Moment Tensor (GCMT) catalogue (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012). The attenuation of 5% damped pseudo spectral accelerations (*Sa*) from these earthquakes is compared to published GMMs for active crustal environments. It is expected that observed ground-motions and attenuation will depend strongly on source parameters, tectonic and geographical features, and site characteristics. Residuals between observed and predicted ground-motions with respect to magnitude and distance are shown to demonstrate each GMMs appropriateness for use in SWBC seismic hazard modelling.

2. Regional Tectonics and Seismicity

Offshore Vancouver Island is a complex collection of tectonic boundaries which contribute to the high-seismicity rates in SWBC (Fig. 1). Where the eastward moving JdF plate moves beneath the NA plate lays the Cascadia Subduction Zone (CSZ), the most widely-known earthquake threat on Canada's West Coast. Although the CSZ is known to produce a devastating megathrust earthquakes (Goldfinger *et al.*, 2008), it is also associated with other types of earthquakes. Large intraslab earthquakes (up to M_W 7.0) are known to occur within the Juan de Fuca plate as it subducts beneath the NA plate (Rogers, 1998). Similarly, as the NA plate is compressed by the subducting JdF plate, crustal stresses in the NA plate increases and is eventually released through shallow, crustal earthquakes (Rogers, 1998; Ristau *et al.*, 2007; Balfour *et al.*, 2011). The largest historical crustal earthquake in SWBC was in M_W 7.3 in 1946 near Port Alberni. This earthquake was felt as far as the Rocky Mountains and caused considerable damages in Comox, Port Alberni and Powell River (Rogers and Hasegawa, 1978).

North of the JdF plate lies the Ex plate, which although was once connected with the JdF plate, now moves independently (Braunmiller and Nábělek, 2002). The relative movement between the JdF and Ex plates, along the Nootka Fault Zone (NTK) produces many earthquakes (Obana *et al.*, 2015). In addition, movement of the Ex plate induces oceanic crustal earthquakes along the Revere-Delwood-Wilson fault (RDW) (Braunmiller and Nábělek, 2002).

3. Data Set and Processing

Time-series data were compiled from the CNSN waveform archive for 86 $M_W \geq 5.0$ events that occurred within SWBC between 1996 and 2015 (Fig. 1). For two of these events (2011-09-09 M_W 6.3 and 2014-04-24 M_W 6.5) data from BC Ministry of Transportation's IA sites were also collected. Altogether 765 independent time histories were compiled for this assessment. Earthquakes in SWBC can be divided into three regions shown by shaded regions in Figure 1: (i) east of CSZ and within the NA; (ii) west of CSZ on and surrounding the NFZ and (iii) west of CSZ and north of the NFZ. All of these regions lie west of Vancouver Island. As a consequence, of the earthquakes analysed, the majority of stations are greater than 100 km from the source. Six events had at least two stations with rupture distances <100 km (Fig. 2).

When possible, site-to-source distances used in GMM calculations were obtained from the local CNSN event locations, while the moment tensor was obtained from the GCMT catalogue. If an event was not in the GCMT catalogue, source parameters were obtained from the CNSN moment tensor database. The majority of earthquakes in SWBC are strike-slip events. Within the dataset, all events have strike-slip focal mechanisms. Reverse- and normal- faulting mechanisms are observed for a small portion of $M_W<5.0$ events. As a consequence, we do not examine the effect of earthquake mechanism on the recorded ground-motions.

Observed ground-motion is strongly dependent on site characteristics, such as soil stiffness, commonly defined by the time-averaged shear-wave velocity of the upper 30 m of the crust (V_{S30}). If V_{S30} has not been specifically measured (which is often the case) the most appropriate NEHRP (National Earthquake Hazards Reduction Program) V_{S30} site condition (Federal Emergency Management Agency, 1994; Finn and Wightman, 2003) is used in GMM calculations. CNSN seismographs are installed on rock, therefore we assume a NEHRP A/B boundary (V_{S30} = 1,500 m/s) at these sites (Atkinson, 2005). IA sites are usually installed near structures or high-consequence infrastructure required for response and recovery (e.g. bridges, tunnels, etc.). For this reason IA sites are assumed to be located at site similar to NERHP C/D boundary (V_{S30} = 360 m/s).

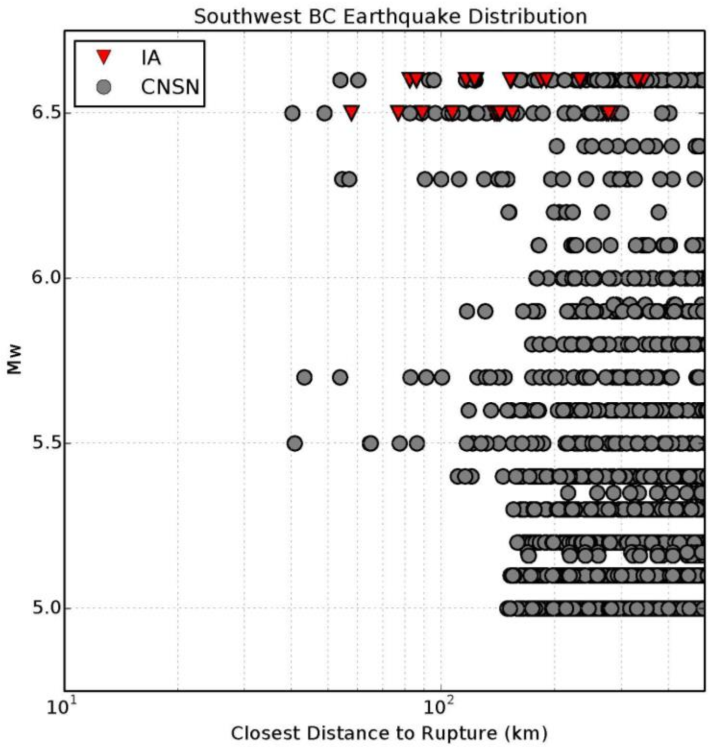

Figure 2 - Magnitude-distance range of earthquake dataset used in this assessment. Red triangles represent recordings at IA stations, grey circles represent recordings at CNSN stations.

The earthquake mechanism, magnitude, and site class are used in GMMs to estimate ground-motion at a range of source-to-site distances. Extended fault rupture properties are not readily available for the events used in this assessment. Therefore the source-to-site hypocentral distance is assumed to be equivalent to the closest distance to the rupture distance (R_{rup}) for all events. Similarly, the Joyner-Boore distance (R_{JB}) is estimated as the epicentral distance. This assumption could introduce errors in measuring site-to-source distances of up to approximately 20 km.

Between 1996 and 2015 there were a number of possible aftershock sequences. For this paper, events within aftershock sequences are not treated differently than other events. Previous studies have shown that there is a systematic difference between short- and long-period ground-motions for events within aftershock sequences (Abrahamson and Silva, 2008; Wooddell and Abrahamson, 2014). The difference between mainshock and aftershock ground-motions will be addressed in future studies.

In total, waveforms from 43 CNSN weak-motion stations and 20 strong-motion stations were used to process observed ground-motions for comparison to commonly used GMMs. Of the CNSN stations, 30 sites were instrumented with broadband seismometers (various makes and models), while the remainder were short-period stations. Although the short-period stations have a limited frequency bandwidth, for the periods assessed they provide sufficient information. Instrumentation at the IA sites varies, but all have the same recording capabilities.

Raw time-histories are corrected for instrument response using instrument response files from the CNSN waveform archive. Low-quality data was initially eliminated by visual inspection. The remaining waveforms were then used in residual analyses if the signal-to-noise ratio at the period considered, was greater than 2.0. All further processing of waveforms was identical to that described in Allen and Brillon (2015).

4. Observations

Observed *Sa* for 86 M_W≥5.0 earthquakes in SWBC were compared to commonly used GMMs for active crustal environments: Zhao *et al.* (2006) (Zea06crust); Atkinson and Adams (2013) (AA13wc); Akkar *et al.* (2014) (Aea14); and Boore *et al.* (2014) (Bea14crust); as well as an offshore model included in Atkinson and Adams (2013) (AA13os). In general, observed ground-motions are notably lower than those predicted by all GMMs assessed in this paper. The majority of earthquakes in SWBC are offshore earthquakes in oceanic crust. Given this, it is expected that GMMs developed using crustal earthquakes would not accurately predict ground-motions from offshore earthquakes. While AA13os better predicts observed ground-motions than AA13wc, most of the improvement is for the longer periods (T>2.0 s).

For the largest earthquake in each of the three seismic regions (Fig. 1) we plot the predicted and observed Peak Ground Accelerations (PGA) and *Sa* at periods of 0.2, 0.5, and 1.0 s (Fig. 3). For the NFZ and RDW events shown in Figure 3a and b, respectively, the difference between the predicted ground-motions is larger than that of the NA crustal event (Fig. 3c). This trend is seen throughout the current dataset, supporting the need to update GMMs used in SWBC.

While the predicted ground-motions for the M_W 6.6 2014-04-24, NA earthquake are high, as expected, they are closer to observed ground-motions than the events further offshore. The NA event was located at 10 km depth, likely within the CSZ accretionary prism. The accretionary prism is expected to be of lower crustal rigidity that the typical crustal environment (Bilek and Lay, 1999). Ground-motions from an earthquake in such an environment may yield lower ground-motions than one in crystalline basement owing to source and path effects. Figure 3d shows observed and predicted ground-motions of a *Mw* 6.3 event near the 2014-04-24 event, but at a depth of 35 km. Due to the depth of the *Mw* 6.3 event, the observed ground-motions for this event appear to be more similar to those predicted by GMMs.

The most recent National Seismic Hazard Model of Canada is based on the GMMs from Atkinson and Adams, 2013. Residuals [$\log_{10}$(observed)-$\log_{10}$(modelled)] for select periods (0.2, 1.0, 2.0 s) for the AA13wc and AA13os GMMs are shown in Figure 4. Median residuals for all periods and R_{rup} are negative. Moreover, at distances of approximately 150 km residuals become increasingly more negative (~50% more). The improvement due to the addition of the offshore GMM is reflected in the residuals shown in Figure 4b, with the most significant improvement at longer periods (2.0 s). Assuming that residuals at R_{rup}<100 km are from events that are considered to occur in an active crustal environment, it is expected that the AA13wc model would have smaller absolute residuals at those distances than the AA13os model. The smaller absolute residuals for the crustal events (i.e. those sites with R_{rup}<100 km) makes the AA13os model appear to be the superior GMM. However, the AA13os model was not intended for use for crustal environments. While using incorrect site characteristics (V_{S30}) may impact the magnitude of the residuals, it is unlikely that improved site characterisation would significantly decrease them. The general over-prediction of the crustal and offshore GMMs suggests that further refinement of these models is needed.

For the GMMs discussed, residuals across the full spectral range are shown in Figure 5. Previously discussed observations and expectations are reiterated in this figure. A theme throughout these residuals is that all GMMs assessed are more suitable for larger (M_W≥6.0) earthquakes. This difference of residual magnitudes above and below M_W 6.0 (Fig. 5a) could in part be due to aftershock sequences embedded within the dataset. It is possible that the M_W<6.0 event set is comprised of mostly aftershocks, which can have different *Sa* than an independent event of the same size (Abrahamson and Silva, 2008; Woodell *et al.*, 2014). The difference in residuals seen for R_{rup} less than and greater than 100 km is likely an effect of the different tectonic environments in which the earthquakes occurred. The model that has the best overall fit for both the distance and magnitude range shown is Aea14 (Fig. 5b). However, for periods greater than 1.0 s for all events, the AA13os model gives near-zero residuals for near-source records. For R_{rup} >100 km there is not one specific model that clearly performs better than the others.

It has been shown that for earthquakes off Canada's west coast local magnitudes (M_L) are 0.62 ± 0.08 smaller than their M_W counterpart, calculated from moment tensors (Ristau et al., 2003). The attenuation of waves travelling through oceanic and continental crust causes the artificially smaller M_L. We expect that this effect also contributes to the ground-motion residuals observed in this study, however, the attenuation parameters have not been directly determined.

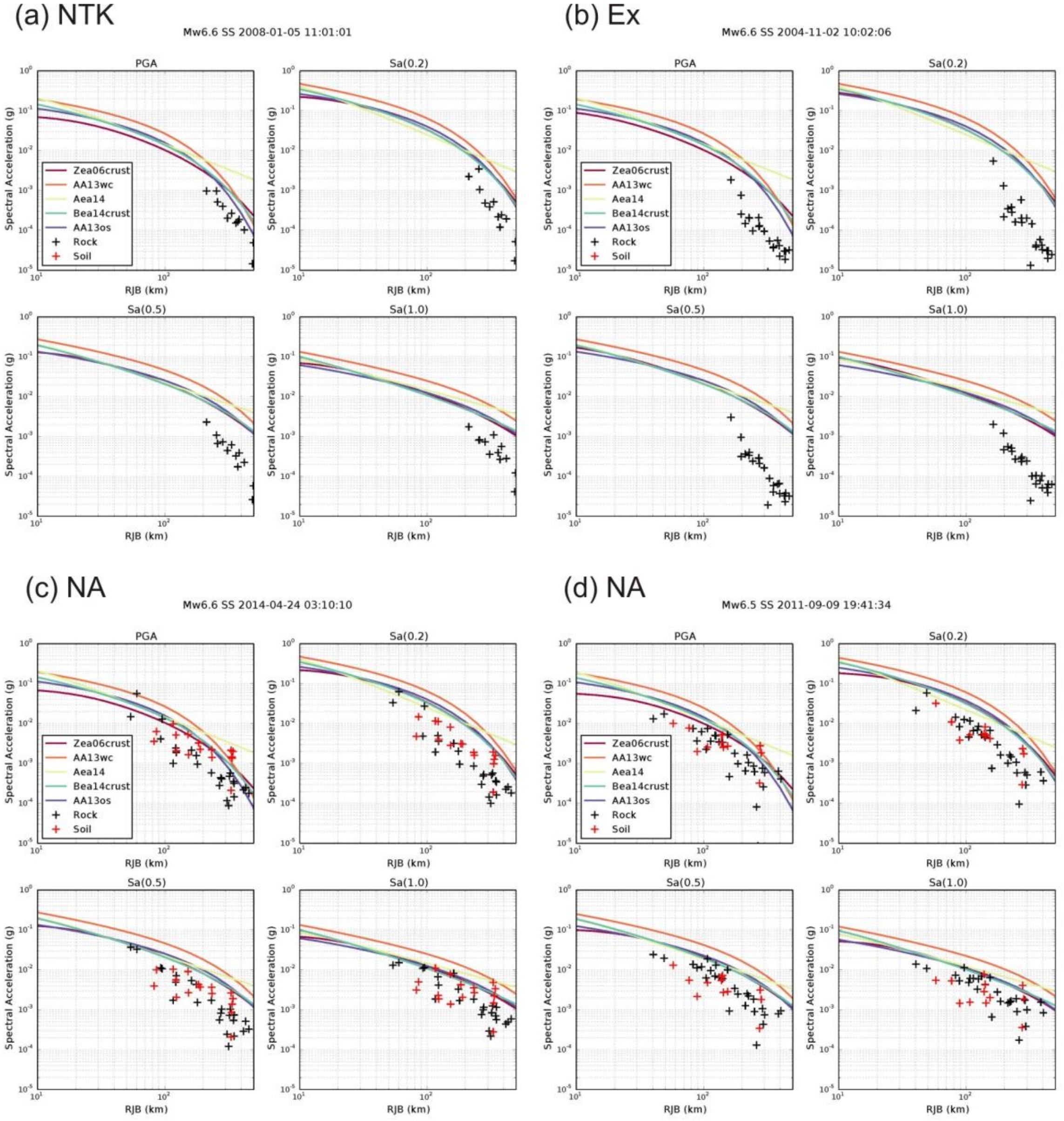

Figure 3 - Attenuation of the geometric mean of 5% damped pseudo spectral acceleration of the horizontal-components for (a) M_W 6.6 2008-01-05 (Ex); (b) M_W 6.6 2004-11-02 (NTK); (c) M_W 6.6 2014-04-24 (NA - shallow); (d) M_W 6.3 2011-09-09 (NA - deep), plotted against well-established GMMs for: Zhao et al. (2006; Zea06crust); Atkinson and Adams western crustal and offshore (2013; AA13wc, AA13os, respectively); Akkar et al. (2014; Aea14); and Boore et al. (2014; Bea14). Soil records are corrected from 360 m/s to a reference site of 1,500 m/s using the equations of (Seyhan and Stewart, 2014) assuming a reference PGA (PGA_r) from Akkar et al. (2014). Note, the Aea14 model is not valid beyond 200 km.

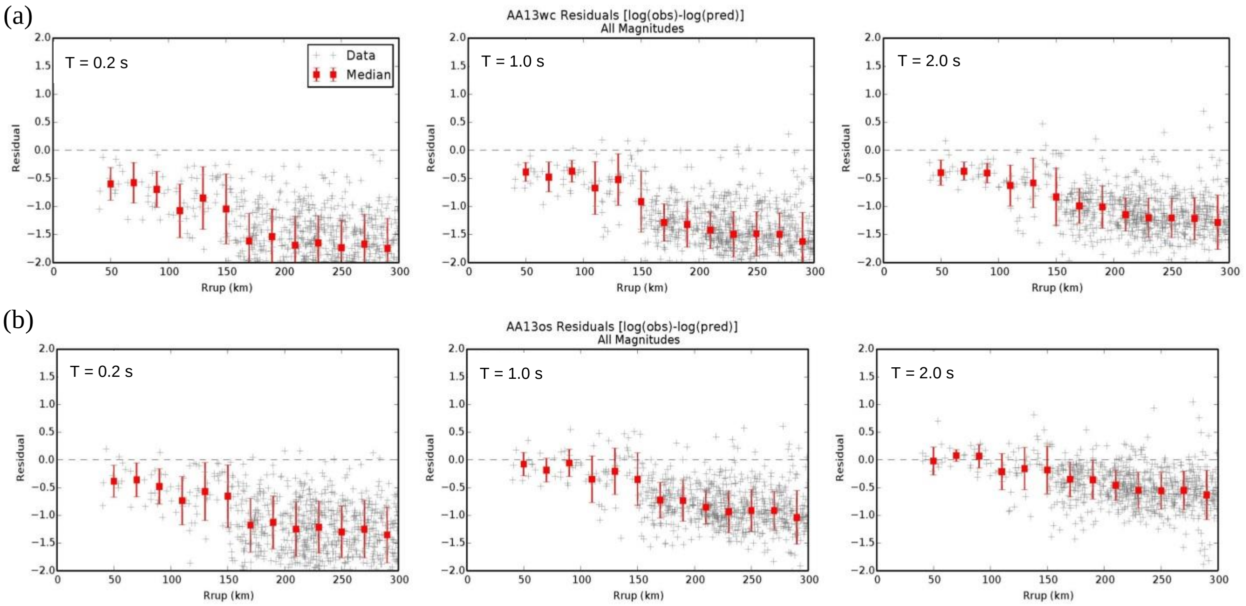

Figure 4 - Mean and standard deviation (red) of residuals (grey) ($\log_{10}$ of 5% damped pseudo spectral acceleration (geometric mean of horizontal components)), from SWBC earthquakes compared to (a) AA13wc and (b) AA13os (Atkinson and Adams, 2013). Ground-motion predictions for magnitude-distance pairs equivalent to rock sites assume a V_{S30} of 1,500 m/s, while Internet Accelerometer (soil) sites assume a V_{S30} of 360 m/s.

5. Conclusions

The high seismicity rate and number of active faults offshore Vancouver Island exposes the population of SWBC to negative impacts of earthquake shaking. To provide a starting point for future seismic hazard modelling in SWBC, we present an assessment of ground-motion amplitudes relative to GMMs implemented in the national seismic hazard model proposed for the 2015 NBCC, as well as alternative GMMs from active crustal regions. Ground-motion recordings from 86 earthquakes of $M_W \geq 5.0$ occurring in SWBC occurring between 1996 and 2015, with moment tensor solutions were assessed. While the offshore model AA13os (Atkinson and Adams, 2013) appears to be more suitable for SWBC at longer periods and larger magnitudes, the Aea14 model (Akkar et al, 2014) behaves consistently well across all periods. The overall observation for all GMMs included in this assessment is that they overestimate ground-motions for shallow offshore earthquakes in SWBC. A number of factors (e.g., source, attenuation, site characteristics) could be contributing to the over-estimation discussed herein and will be investigated in more detail for future generations of the National Seismic Hazard Model of Canada.

The abundance of seismicity and complexity of seismic sources affecting SWBC require more attention than can be presented in this paper. Future work should assess the utility of existing GMMs for use in SWBC and possibly the development of alternative models that better characterize the attenuation from shallow offshore earthquakes.

Miniseed files, earthquake source parameters and spectral-accelerations can be made available from the authors upon request.

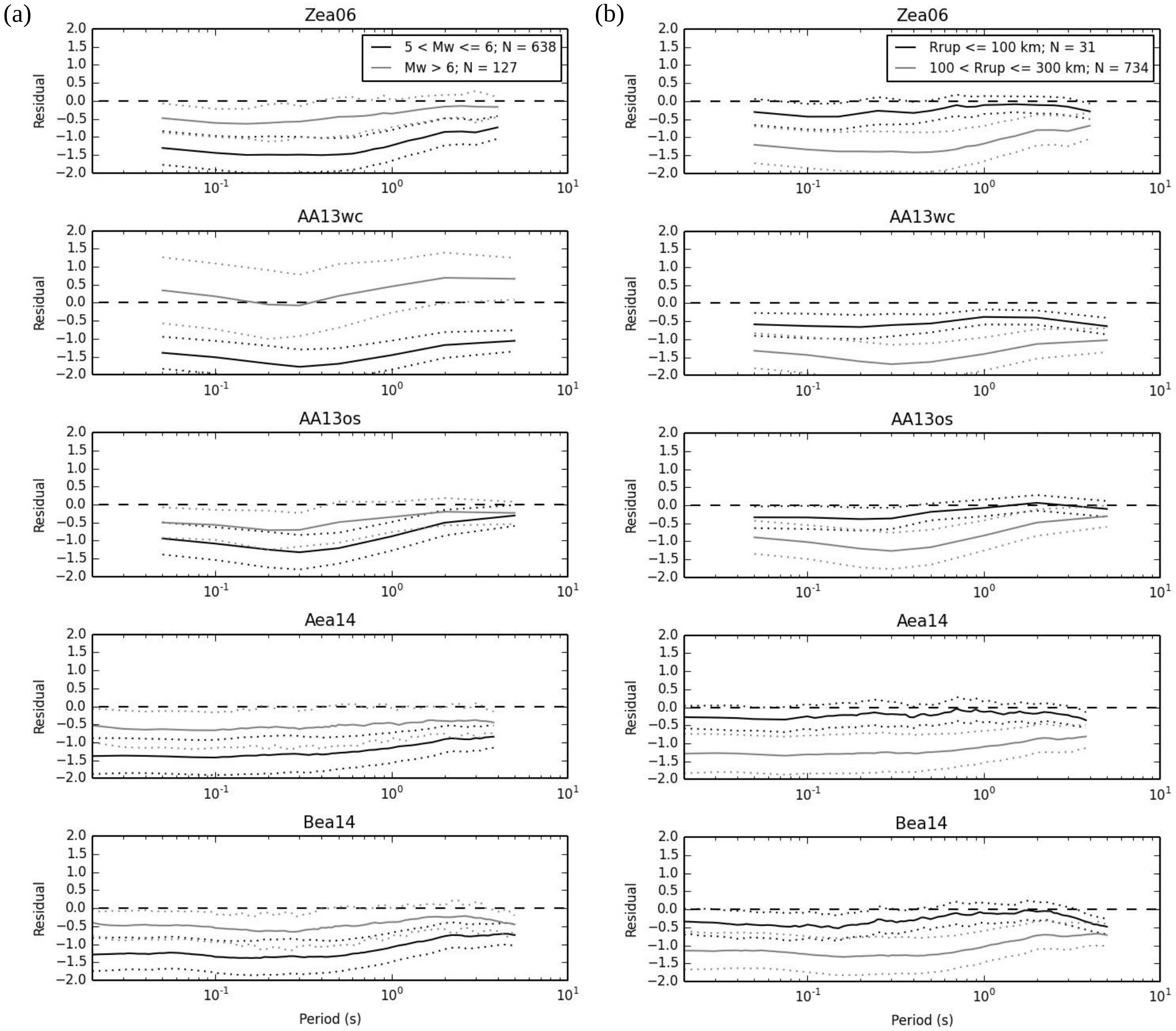

Figure 5 - Residuals ($\log_{10}$ of 5% damped pseudo spectral acceleration from SWBC earthquakes compared to candidate GMMs: Zhao et al. (2006; Zea06); Atkinson and Adams (2013; AA13wc, AA13os); Akkar et al. (2014; Aea14); and Boore et al. (2014; Bea14)) for R_{rup} ≤ 300 km for records binned by (a) M_W (b) R_{rup}. In each subplot, N is the number of records in each bin. Ground-motion estimates for magnitude-distance pairs equivalent to rock sites assume a V_{S30} of 1,500 m/s, while Internet Accelerometer (soil) sites assume a V_{S30} of 360 m/s.

6. Acknowledgements

The authors would like to thank John Adams for helpful discussions and reviewing this paper.

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