17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

SEISMIC HAZARD IN SOUTHEASTERN CANADA: UNCERTAINTY AND CONTROLS ON SEISMIC HAZARD IN A REGION OF LOW-TO-MODERATE SEISMICITY

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Abstract

Despite southeastern Canada being in a stable continental region, large and damaging earthquakes have occurred and will inevitably occur again. Unlike active tectonic regions, there is considerable uncertainty in the location, size and rate of future large damaging earthquakes. Seismic hazard models attempt to understand and quantify their parameters by developing logic trees of possible choices that are combined in a probabilistic framework. For southeastern Canada, three alternative source models are considered based on different philosophical interpretations of long-term seismicity rates in stable intraplate settings. The historical model assumes that the historical catalogue is an adequate representation of long-term seismicity rates. The regional model assumes that present-day seismicity is clustered in areas of past large events (i.e., aftershocks) but that future large events are equally likely to occur in other areas of similar seismotectonic setting. The hybrid model assumes that the historical rates are adequate proxies to predict the M<6.8 earthquakes (which are inferred to represent sustained aftershock sequences of M>6.8 mainshocks) but that regional seismotectonic features govern the occurrence of those mainshocks. This paper discusses how uncertainty is included within the seismic hazard model of eastern Canada, how the estimate of seismic hazard varies for different model assumptions and it explores the major contributors to seismic hazard in Toronto and Montreal.

Keywords: Seismic Hazard, Canada, Intraplate

1. Introduction

Southeastern Canada is within the stable interior of the North American tectonic plate and is far from any active plate boundary. While large parts are relatively aseismic, moderate seismicity exists within distinct bands in the St. Lawrence Valley (including the active cluster in Charlevoix, Quebec), the lower St. Lawrence and western Quebec and eastern Ontario. These earthquakes are largely believed to be occurring in zones of fractured crust, principally on and near Paleozoic rift structures which broke the integrity of the North American craton [1]. While the rate of large earthquakes is lower than in active tectonic regions, the majority of large urban cities occur in or near zones of large historical and pre-historical earthquakes, including a M7 in 1663 in Charlevoix (less than 100 km from Quebec City), a M5.8 near Montreal in 1732, a M6.1 in Timiskaming in 1935, a M5.6 in Cornwall in 1944, a M5.9 in Saguenay in 1988, and several M>6 prehistoric earthquakes in the Ottawa area (Fig. 1). Thus, characterizing the seismic hazard in southeastern Canada is of critical importance to ensure that an appropriate level of earthquake resistant engineering is used.

The most recent assessment of seismic hazard in Canada, the 6th Generation Seismic Hazard Model of Canada (CanadaSHM6) was completed in 2019 and is expected to be formally released in 2020. It is also currently proposed as the source of design values for the 2020 edition of the National Building Code of Canada (NBCC). With the new model, estimates of seismic hazard have increased on the order of 50% in southeastern Canada [2] primarily due to updates in the ground motion models [3][4]. Characterizing the statistical distribution and uncertainty in the new hazard values is important both from the building code perspective (which typically relies on a single representative number, i.e., the mean), and for improving our understanding of the principal controls on hazard values for southeastern Canada.

The 2005 and 2010 editions of the NBCC (corresponding to CanadaSHM4) used the median hazard measure and little effort was made to evaluate and investigate the distribution in hazard about the median. The 2015 edition of the NBCC changed from median to mean hazard, thus incorporating some portion of the spread of the hazard results (quantiles, also termed percentiles or fractiles). Adams and Halchuk [5], discussed the distribution about the median for CanadaSHM5 hazard estimates, and showed that mean hazard typically corresponded to the 70th to 80th percentile in low- to moderate-seismicity regions where there is greater uncertainty in the parameters, and argued that lognormal distributions could be used to fit the spread in hazard estimates.

In this work, we discuss how uncertainty is parametrized within CanadaSHM6 for southeastern Canada. In particular, we discuss the implementation of alternative estimates for seismic sources, recurrence parameters (including maximum magnitude), and ground motion models. Lastly, we present how these uncertainties in model parameters map to uncertainty in hazard by calculating the quantiles of hazard for Toronto and Montreal, the two largest cities in eastern Canada.

2. Seismic source characterization

2.1 Seismic source models for the activity of eastern crustal earthquakes

The fourth generation model (CanadaSHM4) characterized the epistemic uncertainty in seismic source characterization by including two seismic source models. The historical model (**H**) was based on historical clusters of seismicity implying that contemporary local activity is a good predictor of future large earthquakes. By contrast, the regional model (**R**) was based on the assumptions that large seismotectonic structures set the local rate of significant earthquakes. Arguments for the **R** model include the 1988 M 5.9 Saguenay earthquake which occurred in the Saguenay graben, a failed arm of the Iapten rift, an area that had been monitored for over five decades before 1988 without detecting any event larger than M~2.5. For each locality, the higher hazard from either the **H** or **R** model was used for design in the NBCC.

Several authors have proposed that the historical clusters of increased activity in fact represent aftershocks of a large initiating event, albeit occurring over a very long time perspective [1][6][7], and others have incorporated similar ideas into probabilistic models (e.g., [8]). For example, the activity in Charlevoix, the best known and most active cluster in eastern Canada, contains four M>6 historical events since 1663, and under this hypothesis, these earthquakes are likely consequences of the large initiating earthquake in 1663 of magnitude ≥ 7.

Our expectation is thus that active clusters will continue to produce earthquakes, but perhaps only to some upper magnitude threshold reflective of them being aftershocks, and that smoothing the activity rate over large seismotectonic zones is likely only appropriate for larger earthquakes. With this paradigm, historical seismicity would govern the location of earthquakes for magnitudes below a set threshold while regional seismotectonic features would govern the location of earthquakes for magnitudes between the threshold and the maximum possible magnitude (M_{max}). For CanadaSHM5, this model (termed the hybrid, **HY**, model) was implemented using a threshold of M6.75. The hazard is relatively insensitive (≲10%) to thresholds in the range 6.5 to 7.0. Note that for Charlevoix the model's rate of M6.8 is sharply lower than for M6.7, while in low-seismicity segments of IRM, the rate for M6.8 (determined regionally) is higher than for M6.7 (determined from local low-magnitude seismicity), which is a non-intuitive result.

Support for the hybrid model comes from a number of sources. Firstly, although the rate of M≥4 earthquakes around Trois Rivières is very low, smaller earthquakes (magnitude 1-2) outline the seismogenic rift structures on which the large events are expected to occur (Fig. 1). Secondly, large events (disproportionate in size to the preceding activity) have occurred in low-seismicity regions (e.g., the Saguenay earthquake). Determining the rate for the larger magnitude events within the **HY** model is a challenge, because they are by definition rare. Adams [9] described a process whereby using a strong declustering of the catalog (400-year time window and a 50-km distance window) gave the rate of M≥6.8 earthquakes as ~0.01 p.a. for eastern Canada; this rate was then distributed between the regional seismotectonic zones based on their rate of M3 earthquakes.

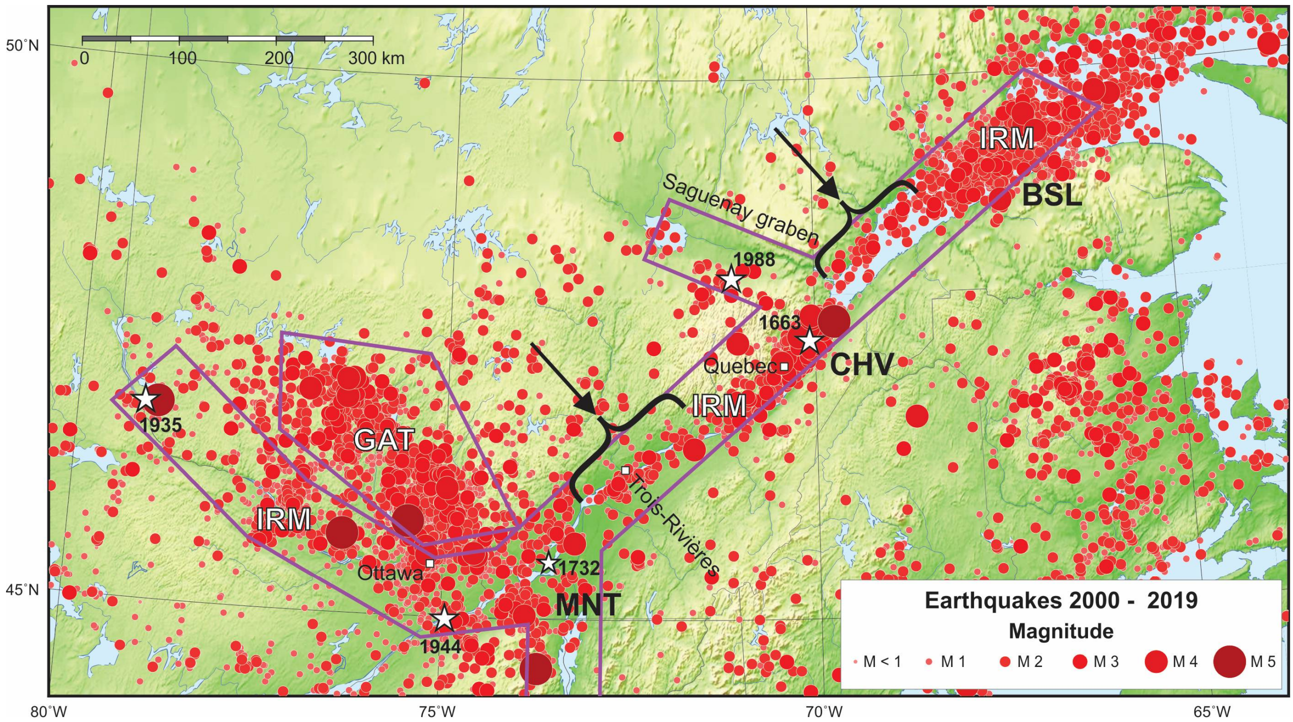

Fig 1 - Contemporary small-magnitude seismicity in southeastern Canada and the outline of the Gatineau (GAT) and Iapeten rifted margin (IRM) sources. Note how the seismicity of low-activity regions (black arrows) fills in the trend of the Iapetan rift structures between the active clusters near Montreal (MNT), Charlevoix (CHV) and the lower St. Lawrence (BSL).

The CanadaSHM6 model, which retains the seismic source model from CanadaSHM5, thus consists of the three alternative source models described above:

- a historical model (**H2**, weight = 0.4) updating the CanadaSHM4 **H** model,
- a regional model (**R2**, weight = 0.2) updating the CanadaSHM4 **R** model, and
- a hybrid model (**HY**, weight = 0.4) which uses the H2 model with M_{max} of 6.8, and then adds regional seismotectonic sources (like the **R2** model) just for events from M 6.8 up to the same M_{max} as the **H2** model.

The **R2** model is given half the weight of the others and is included partly as a hedge that the original hypothesis was correct, and partly as a damping influence on model evolution with time.

Figure 2 compares short-period 2%-in-50 year seismic hazard estimates using CanadaSHM6 for the three source models and their weighted combination. The pattern and effects are generally similar for longer periods. Although the region of hazard is broadly the same, the details within it differ in each model. The clearest difference is between **H2** and **R2** model, where the high hazard near Charlevoix from **H2** is smoothed out along the rift structures in the **R2** model. The **HY** model is intermediate, more generally similar to the **H2** model (because magnitudes below 6.75 make the dominant contributions to 2%-in-50-year hazard), but with the hazard near Charlevoix smoothed out. As expected, the hazard results using all three models in a probabilistic framework has features of all three models.

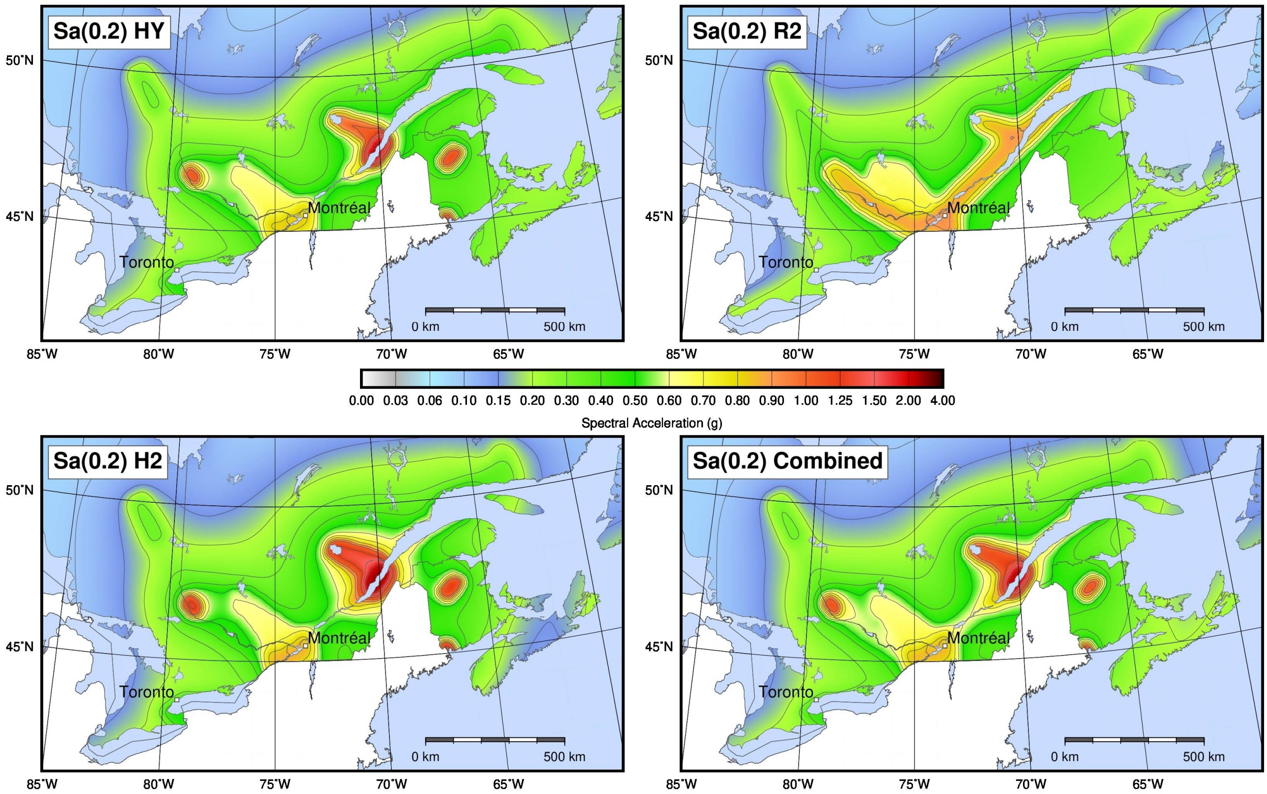

Fig. 2 - Hazard estimates for Sa(0.2) mean hazard at 2%/50 years on V_{S30} = 450 m/s computed for each of the eastern source models, and for their weighted combination in the probabilistic model.

2.2 Earthquake catalog and magnitude-recurrence parameterization

For all sources in the southeastern model, the truncated Gutenberg-Richter (G-R) distribution is used with three separate activity rates (*a* and *b* pairs) and three M_{max} values to represent the rate of earthquakes and its uncertainty. Below we briefly describe the catalog and the parameters used to estimate the magnitude-recurrence of earthquakes in southeastern Canada.

2.2.1 Earthquake catalog and declustering

Earthquake magnitudes in the historical catalog [10] are converted from local magnitudes to estimated moment magnitudes using regional relationships [11]. The catalog extends from the earliest earthquake to 2014, and for each source the dates since which the catalog is considered complete for earthquakes above certain magnitudes are established based on expert judgement. In this way the long complete history of the larger earthquakes, and the shorter complete history of smaller earthquakes can be combined. The catalog is not declustered, reflecting firstly that declustering algorithms with California-sourced parameters are probably not appropriate for the low-seismicity regions that comprise most of Canada, and secondly that (as discussed above) the active sources of eastern Canada may well represent long-duration aftershock sequences that we consider are better treated by different models of the seismic source.

2.2.2 Maximum magnitude (M_{max})

The maximum magnitude (M_{max}) represents the largest probable earthquake. The seismic hazard integration includes the shaking contributions of earthquakes up to the M_{max} (it is the largest unconsidered earthquake) and in almost all cases M_{max} is an extremely rare event. The largest historical event in an eastern Canadian seismic source zone (recorded history of ~250 years) is roughly 10 times more common than the 1/2475 year event (i.e., return period of 2%/50 years) and the value for M_{max} should be at least one magnitude unit larger (for a typical *b*-value and assuming the statistics can be applied appropriately). However, in regions of low- to moderate-seismicity such considerations place only lower limits on M_{max}, and in our view it is preferred to estimate M_{max} from global analogs (under the assumption of ergodicity) because of the limited data from which to constrain the local value.

For each source, a three-branch distribution for M_{max} has been used with weights of: lower = 0.3, central = 0.6, and upper = 0.1. The very low weight on the "upper" represents the philosophy that if the central estimate is properly chosen, there is a small chance that it should be even larger. Note that for some zones even the lower M_{max} values are upwards of two magnitude units larger than the largest nearby historical event. Based largely on global analogs, M_{max} (lower, central, upper) for southeastern Canada (Fig. 3) is assigned from one of following three classes:

Class I. M_{max} = 6.8, 7.0, 7.2; stable craton
Class II. M_{max} = 7.0, 7.3, 7.6; continental regions without significant Phanerozoic rifting (e.g. WLO)
Class III. M_{max} = 7.4, 7.8, 8.0; continental regions that are part of a rifted margin (e.g., CHV)

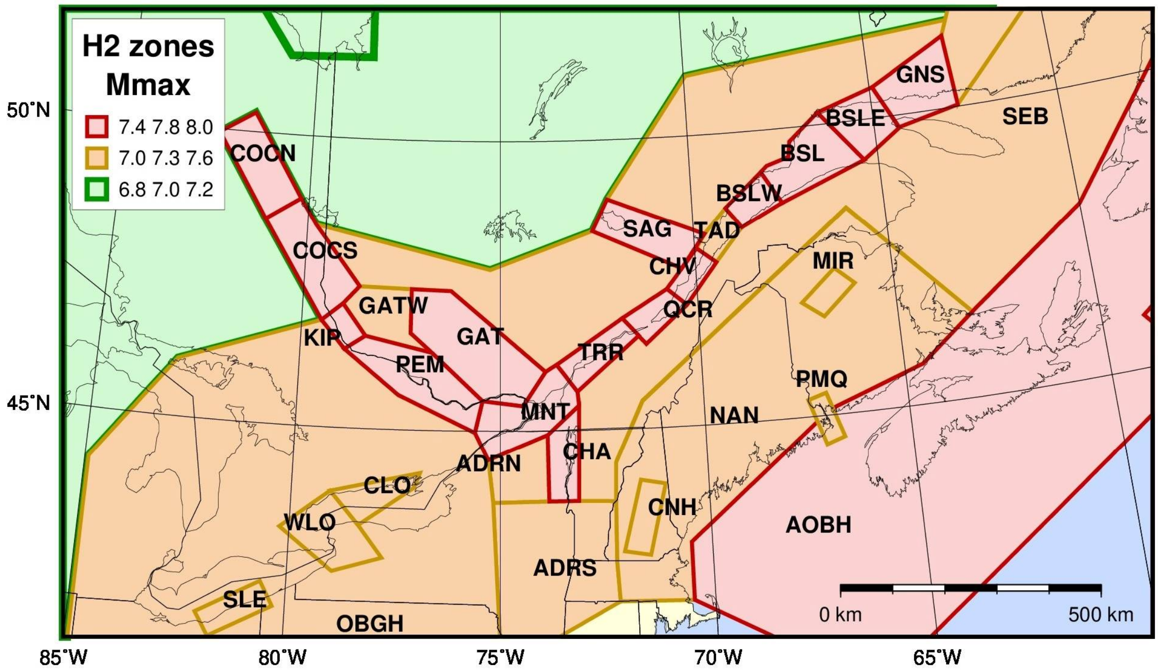

Fig. 3 – Variation in M_{max} for the **H2** source model. M_{max} values in legend represent the lower, central, upper alternatives. The **HY** and **R2** source models largely follow the same spatial distribution for M_{max}.

In most places, earthquakes just a little smaller than M_{max} make very small contributions to the seismic hazard at probabilities relevant for the Canadian building code (i.e., less than 2%/50years), especially at short periods. The chief exception is in Charlevoix, where a high *a*-value combined with a low *b*-value result in important contributions from near the M_{max} for the **H2** model (but less so for the **HY** model).

2.2.3 Magnitude-recurrence parameters

For each source, magnitude recurrence parameters are fitted to the rates of earthquakes determined from the Seismic Hazard Earthquake Epicenter File (SHEEF, [10]) catalog using the maximum likelihood method and considering the years for which the catalog is complete for each magnitude [12].

Three branches are considered for the *a*- and *b*-values, a central branch weighted 0.68, and upper and lower branches weighted 0.16 that represent the central *a* and *b* values scaled by 1.73 times the standard deviation of the central values (i.e., a 3-branch discretization of a normal distribution). For each branch, three choices for M_{max} are used, giving a total of nine possible alternative magnitude recurrence curves. Representative curves, including the underlying earthquake rates are shown in Fig 4. Of the three representative sources shown, GAT (near Montreal) represents a well-behaved curve that is well constrained from the data, WLO (near Toronto) is poorly constrained, and lastly, CHV which is rich in data but poorly behaved (the recurrence parameters were adjusted from their statistical values to better fit the observed rate of M>5 earthquakes).

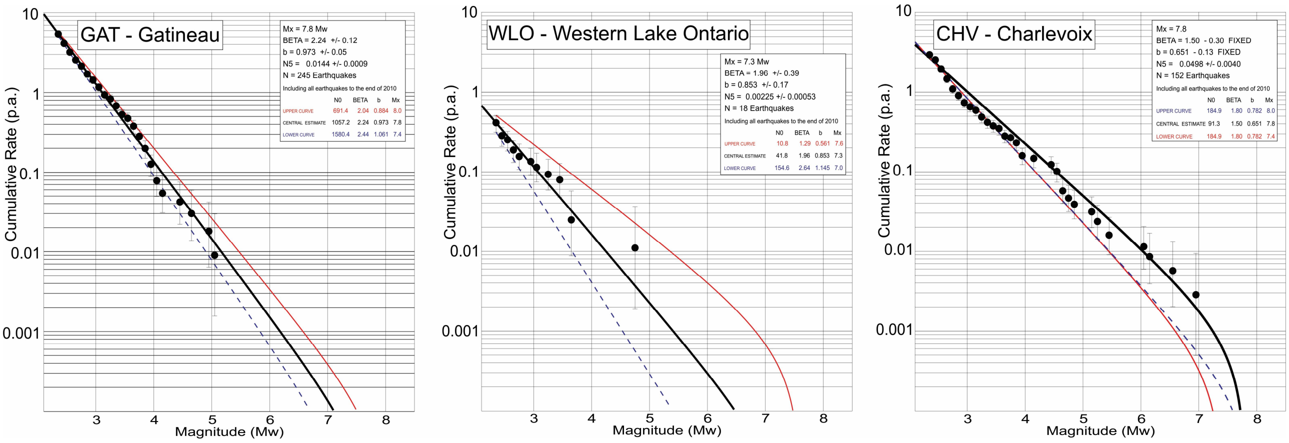

Fig. 4 – Fitted magnitude recurrence curves for three representative sources. Recurrence parameters for each of the curves is included in the inset. For each source, three of the nine curves are shown to depict the lower bound (dashed line; lower *a*, upper *b* and lower M_{max}), central estimate (black solid line; central *a*, *b* and M_{max}) and upper bound (red solid line; upper *a*, lower *b* and upper M_{max}). Note the different choices imposed for the CHV magnitude recurrence curves.

3. Uncertainty in hazard estimates

A key parameter in seismic hazard assessment, especially in intraplate regions, is the understanding and implementation of aleatory and epistemic uncertainty. A larger uncertainty leads to an increase in the mean hazard. The aleatory uncertainty represents the uncertainty associated with the inherent randomness of future events that cannot be reduced by the collection of additional information. It is most often included within the ground motion models (GMMs) as the standard deviation (sigma) about the median ground motions, but is also frequently included for other parameters which exhibit aleatory variability such as the depth of earthquakes and the earthquake rupture orientations and mechanisms. Epistemic uncertainty represents the uncertainty due to a lack of data and knowledge and is typically characterized by including alternative models or estimates of key parameters within a logic tree framework (e.g., the magnitude recurrence parameters discussion in section 2.3). The logic tree for CanadaSHM6 model (Fig. 5) is similar to CanadaSHM5 except that depth was moved from epistemic to aleatory and CanadaSHM6 has many more branches (individual paths within the logic tree) as a result of increasing the number of GMMs from 3 to 16. We briefly describe the GMMs used in eastern Canada (section 3.1) and follow this by an examination of the epistemic spread in hazard for several key localities (section 3.2).

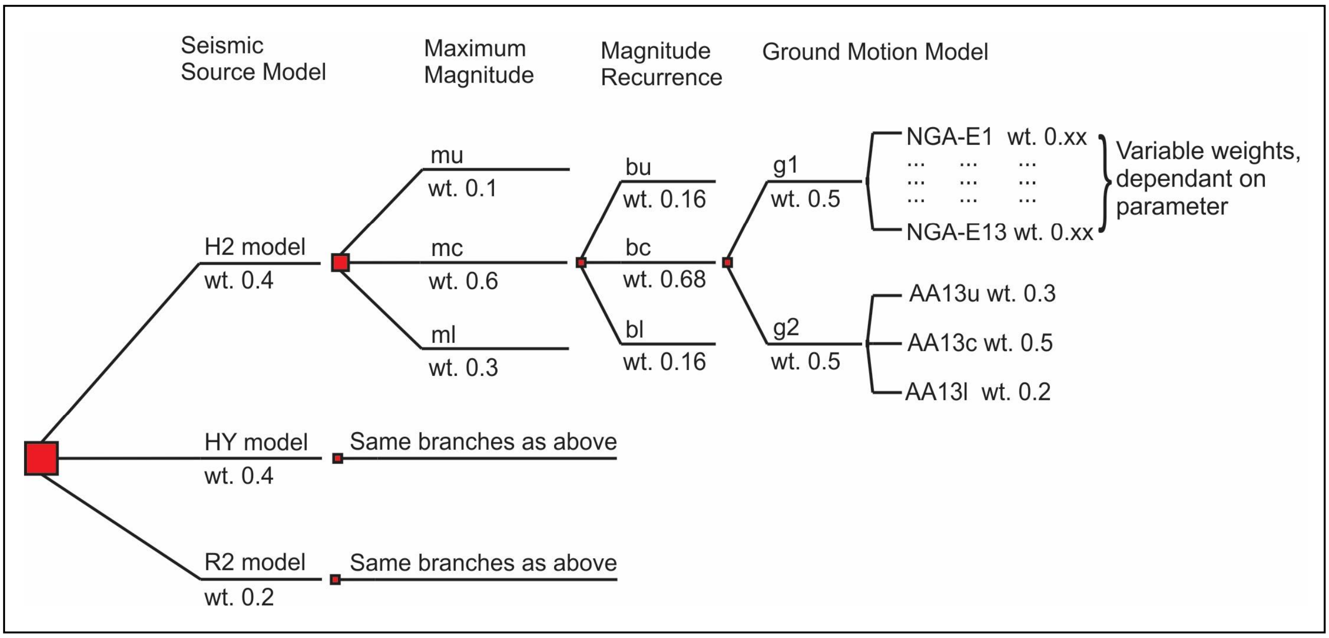

Fig. 5 – Logic tree in CanadaSHM6 for eastern Canada. The weighting for the NGA-East GMMs is period dependent following the recommendations of [13].

3.1 Ground motion models

The GMMs implemented in CanadaSHM6 are described in the companion 17WCEE paper [4]. For completeness, we briefly summarize below the underlying issue in estimating ground motion models for eastern Canada.

The NGA-East project [14] compiled ground motions from central and eastern North America (CENA) with an aim of developing ground motion models for CENA for use in probabilistic seismic hazard analysis. Figure 6 shows the distribution of recorded ground motions from the 89 earthquakes included within the NGA-East project, where the dashed red line indicates the population of most importance to estimate seismic hazard in eastern Canada. Clearly, there is very limited data from which to constrain the range of possible ground motions for the magnitude and distance ranges of most significance, and therefore NGA-East relied heavily on modelling (non-empirical approaches) to estimate the shaking from large-magnitude earthquakes. Nevertheless, the epistemic uncertainty in GMMs in eastern Canada remains high. For CanadaSHM6 we use a 50:50 weighting between the NGA-East-13 GMMs [13] and the GMMs of CanadaSHM5 [15] resulting in a total of 16 possible GMMs for eastern Canada.

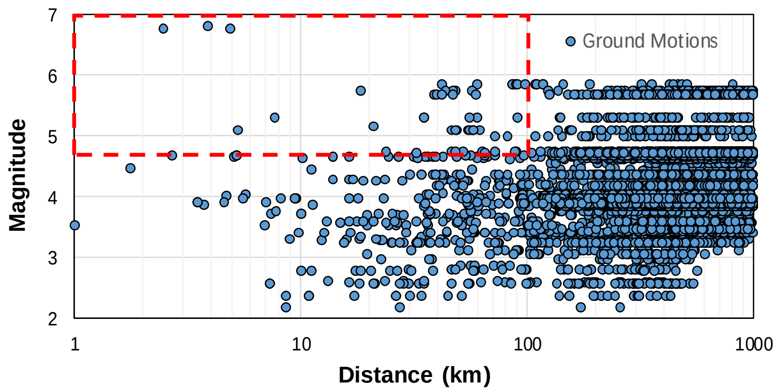

Fig. 6 – Ground motion observations (n=9382) from the NGA-East database [14] for 89 earthquakes. Dashed red line indicates population of greatest relevance for seismic hazard assessment.

3.2 Spread in hazard estimates

The logic tree for eastern Canada (Fig. 5) results in 432 (=3x3x3x16) realizations. In Figure 7, we show a stacked histogram of all of the realizations of the 2%/50 year Sa(0.2) hazard for Montreal. In each quadrant, the stacked bars are coloured by each of the branching levels in the logic tree, the mean hazard is indicated with a dashed black line, and the median of each subset is marked with a colored vertical arrow (Fig. 5). The distribution of realizations appears to follow a normal distribution (in log space) and thus the mean hazard tends to be at a higher percentile than the median. In terms of the distribution of hazard as a function of the source models (Fig. 7A), the **H2** and **HY** produce similar hazard values for Montreal while the **R2** model tends to produce larger hazard values (as can also be inferred by inspection of Figure 2). For M_{max} (Fig. 7B), the hazard is not overly sensitivity to differences between the three alternatives for M_{max} (i.e., all three values are similarly distributed). In contrast, for the *a*-*b*-values (Fig. 7C), the hazard is sensitive to the choice where the upper branch (*bu*) biases the hazard higher while the lower branch (*bl*) biases it lower. For the GMMs (Fig. 7D), the NGA-East-13 predict higher hazard values. Note that while the relative contributions between the three seismic source models for Montreal (Fig. 7A) are not necessarily representative for all localities in eastern Canada (by examination of Fig. 2), the general pattern in the relative contributions to hazard between recurrence parameters and the GMMs is expected to be broadly similar for large regions in southeastern Canada.

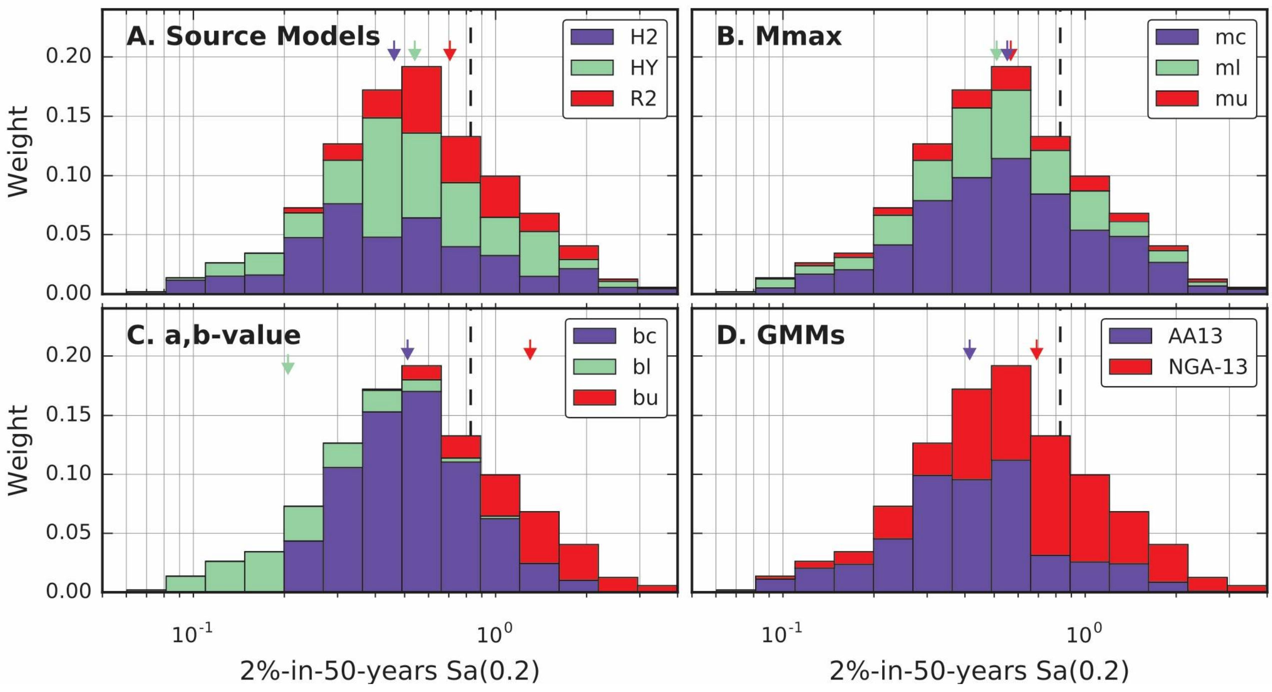

Fig. 7 – Stacked histogram of all realizations of the 2%-in-50-years Sa(0.2) hazard (V_{S30} = 450 m/s) for Montreal coloured by each branching level of Figure 5. Dashed black line marks the location of the mean hazard. Colored arrows mark the median hazard of each subset.

The hazard curves of all realizations (and their weighted mean) generated by OpenQuake v3.3 [4]17] for Toronto (representative of a low hazard site, Fig. 2) and Montreal (representative of a moderate hazard site, Fig. 2) are shown in the top panel of Figure 8. Note the large range of possible values across all probabilities. Despite this, national assessments of hazard and the building code typically only use a single value (per shaking parameter) to represent the seismic hazard. Retrospectively, Adams and Halchuk [5] presented the distribution for the CanadaSHM5 hazard results at seven localities across Canada. They also showed that the distribution was approximately lognormal, discussed step-deviations about the lognormal curve, quantified the spread of the distribution in terms of the standard deviation of the $\log_{10}$ values, and showed that the spread was large in

Toronto, moderate in Montreal, and tended to be smaller in western Canada. In Figure 8, we show a comparable analysis from CanadaSHM6 for Toronto and Montreal. In the middle panel we show the quantiles of the 2%/50 Sa(0.2) hazard (calculated by OpenQuake), and below it the normalized histogram. We also include both the cumulative distribution and probability density lognormal fits to the data. As expected, lognormal distributions provide good fits to both curves. Note that the curves at low shaking levels (i.e., at high probability levels) are poorly constrained due to the lower cut-off magnitude (M_{min}) of M4.8 [16] CanadaSHM6 adopted for engineering reasons.

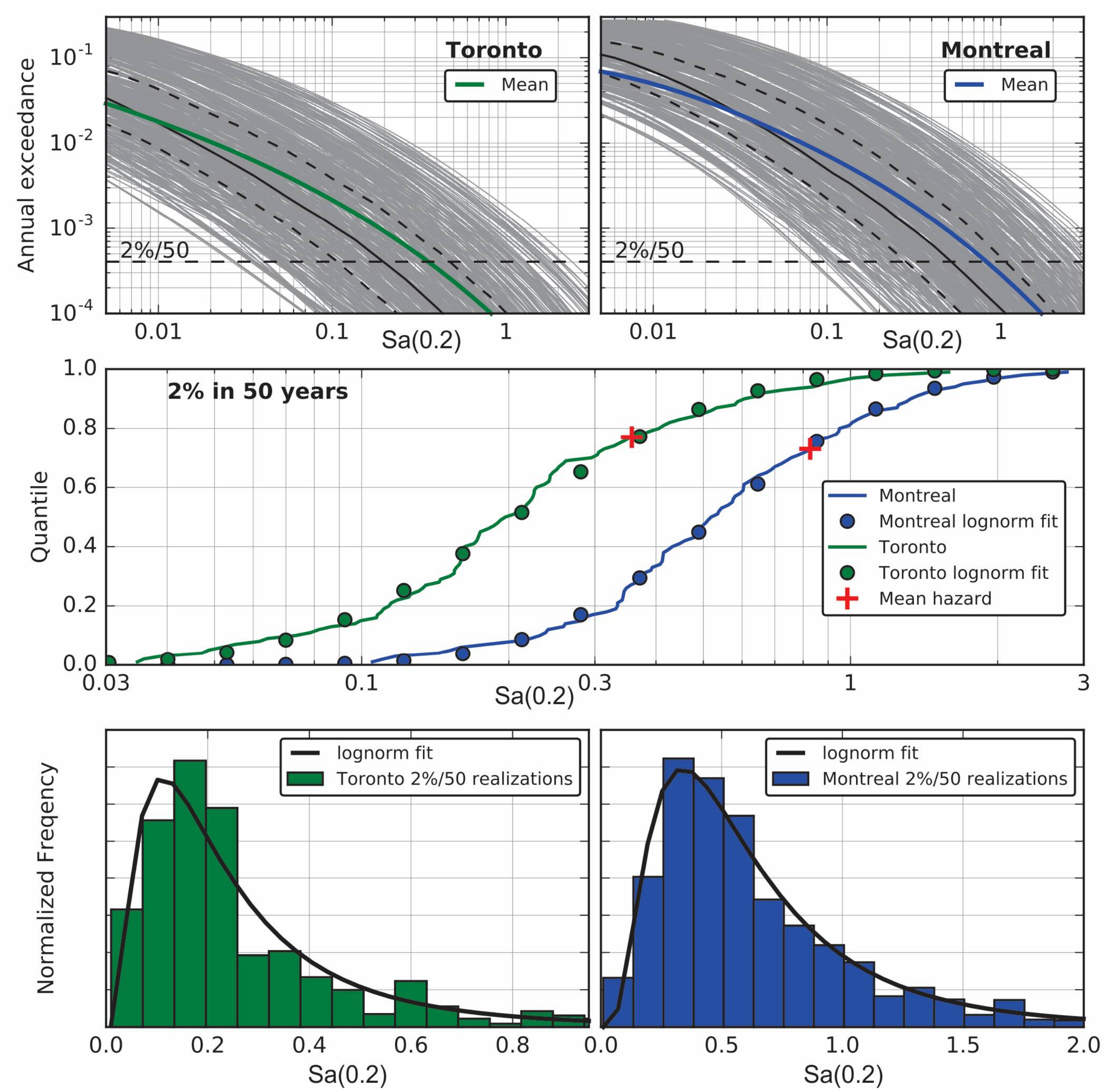

Fig. 8 – Distribution of hazard curves (top panel), quantiles (middle) and probability density distribution of the realizations (bottom) for Toronto and Montreal for Sa(0.2) at V_{S30} = 450 m/s. Solid and dashed lines in top panel represent the median, 16th and 84th percentiles.

A lognormal function is typically expressed with parameters μ and σ, where e^{μ} is the median and σ is the standard deviation of the distribution in natural log units. For Sa(0.2) at 2%/50yr in Toronto, e^{μ} is equal to 0.21 g and σ is 0.79, and in Montreal e^{μ} is equal to 0.53 g and σ is 0.67. As an example of application of these values, one could calculate the 84th percentile of hazard in Toronto and Montreal as 0.45 g and 1.15 g (compared with the actual computed values of 0.475 g and 1.06 g; the difference in part representing the crudeness of the 432-branch epistemic model). The standard deviation (slope of the lognormal curve) is higher in Toronto mainly due to the increased uncertainty in determining the magnitude-recurrence parameters from low-seismicity sources such as WLO. The mean Sa(0.2) hazard for Toronto (0.357 g) and Montreal (0.827 g) falls on the 0.77 and 0.73 quantiles, respectively, reflecting how mean hazard is affected by the uncertainty (spread) in hazard estimates.

Both Canadian and U.S. seismic hazard maps have the same goal of providing mean hazard at 2%/50 year for a range of Sa(T), and it is to be hoped that their models reflect a similar amount of epistemic uncertainty. Lee et al. [18] used an innovative logic tree sampling to replicate the 2014 U.S. National Seismic Hazard Mapping Project (NSHMP) mean hazard curves and to quantify their uncertainty. Their result most comparable to ours above are for peak ground acceleration (PGA) at 2%/50yr on Site Class B/C ($V_{S30} \approx 760$ m/s) at Memphis which has a σ of 0.4, considerably smaller than our value of 0.67 for Montreal. We are uncertain if the low epistemic spread is driven by the dominant contribution of the New Madrid seismic zone, if it would be typical of other eastern sites (e.g., Boston), or if it is in fact due to different amounts of epistemic uncertainty in the two models.

A standard deviation of 0.73 (i.e., the average for short-period at Toronto and Montreal) reflects an uncertainty of about a factor of two in the hazard values, which in our view is reasonable given the uncertainty in the considered parameters. The level of uncertainty is seldom adequately communicated to the users of seismic hazard products who work with single-value measures such as the mean rather than the full distribution. It is also likely insufficient to use a single national spread parameter (implicit or explicit) to determine the margin against collapse. For sites with the same estimated mean hazard, identically designed and constructed structures will have different failure probabilities according to the standard deviation of their site's hazard values.

4. Summary

There is considerable uncertainty in seismic hazard estimates for intraplate regions such as southeastern Canada due to the lack of both ground motion and earthquake rate data from which to constrain key model parameters. The 6th Generation Seismic Hazard Model of Canada, incorporates epistemic uncertainty in the definition (and philosophy) of seismogenic sources, maximum magnitudes, recurrence parameters, and ground motion models. While mean hazard is often the only parameter communicated (and used), there is considerable spread in hazard values. A detailed look at the spread in uncertainty for two important localities in south-eastern Canada, Toronto and Montreal, revealed the expected differences between them. Overall, the epistemic uncertainty in median hazard estimates is roughly a factor of two at short periods.

In Canada, the quantiles or spread in hazard are often only considered for high-importance sites such as nuclear power facilities, but, with the increasing move to performance based seismic design, incorporating the full spread in hazard can yield more reliable (and probabilistic) estimates of building performance. The limited work presented herein suggests that lognormal distributions fit the data remarkably well. Communicating and distributing the median and log standard deviation of the hazard results in addition to the mean values could allow for a greater appreciation/awareness of epistemic uncertainty and its consequences for hazard results in eastern Canada.

5. Acknowledgements

We thank our numerous colleagues at Natural Resources Canada, in particular Nicholas Ackerley for his suggestions on aspects of visualizing the hazard uncertainty and to Allison Bent for her internal review.

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