BENCHMARKING RECENT PSHA APPROACHES

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Abstract: Seismic hazard assessment (SHA), or analysis, plays a crucial role in building design and informing decision making for the mitigation of seismic risk. In the last decades a large number of studies in probabilistic seismic hazard assessment have been published where different criteria have been used for characterizing the source zone model, for selecting the most suitable ground motion models in the study area, for computing hazard itself, etc. Therefore, it is important to check whether the output of a seismic hazard study is compatible with the input, and to compare approaches and software packages used in SHA.
The aim of the present study is to analyse three approaches for probabilistic seismic hazard assessment and their associated software packages: OpenQuake, the most recent software for seismic hazard and risk assessment (Crowley et al, 2013; Pagani at al., 2014); M3C (Musson, 1999; Musson et al., 2009) and EqHaz (Assatourians & Atkinson, 2013), based both on Monte Carlo simulations to calculate the hazard. The comparison is made in terms of methodology, computer performance of the software packages and hazard results, including hazard curves and maps.
The main conclusion from the present work is that if the input parameters are identical, the outputs from any type of approach for seismic hazard analysis have an excellent agreement. Results computed from M3C and OpenQuake are very similar to each other; whereas, the discrepancies between EqHaz and the other two software packages are explained by inherent features of the code EqHaz.

1. Introduction

Since the second half of the Seventies a large number of probabilistic seismic hazard assessments have been published (e.g. for review Reiter, 1990; McGuire, 2004; Abrahamson, 2000). In these studies different criteria are used for characterizing the seismic source zone model, defined by source geometry and source parameters (e.g. recurrence statistics, maximum magnitude, rupture geometry), for the selection of the ground-motion prediction equations (GMPEs) in the study area, and for technical aspects to encode the selected method (e.g. programming language and format of I/O). Furthermore, different methods and software packages exist for computing hazard itself, e.g. EQRISK by McGuire (1976) and FRISK by McGuire (1978), SeisRisk by Bender & Perkins (1982), NSHMP by Frankel et al. (2002), OpenSHA by Field et al. (2003), EQRM by Robinson et al. (2006), M3C by Musson (1999, 2009), CRISIS by Ordaz et al. (2013), EqHaz by Assatourians & Atkinson (2013) and OpenQuake by Pagani et al. (2014).
From a methodological point of view, approaches for SHA can be performed either deterministically or probabilistically (Abrahamson & Sheldock, 1997). Deterministic seismic hazard assessment (DSHA) considers a single earthquake scenario, usually the largest in the area, to model the ground motion in the site under investigation (Reiter, 1990). The outcome of DSHA is a single ground-motion for each analysed scenario (Abrahamson, 2000). Probabilistic seismic hazard assessment (PSHA) identifies not only the largest earthquake, but all possible earthquake scenarios affecting the area, including all possible combinations of magnitudes and distances. Then, the ensemble of earthquakes is used to estimate ground motion parameters in probabilistic terms and, hence, the main outcome is a seismic hazard curve (Abrahamson, 2000). Nowadays, PSHA is the principal methodology for assessing seismic hazard in a specific region, or site. The most common procedures for

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PSHA are: a) the Cornell-McGuire (or conventional) PSHA; and 2) a Monte Carlo based PSHA (or stochastic approach for PSHA). The former, developed by Cornell (1968) and later modified by McGuire (1978, 2004), is an analytical approach based on the integration of probabilistic functions over a certain number of variables (McGuire, 2004; Bommer & Abrahamson, 2006). The latter is based on simulating the earthquake generation processes many times as well as the generation of their ground motion using a Monte Carlo process (i.e., controlled use of random numbers) (Musson, 1999, 2009). The outcome is obtained from the observation of the results (Musson, 2000). Although the Cornell-McGuire method and the stochastic approach for PSHA are different, they provide the same output given the same input (Musson, 1998).

Software packages for PSHA published in the last couple of years (e.g. OpenQuake and EqHaz) include the most recent advances in the methodology. Their publication prompts the present work. Its goal is to benchmark the code M3C, developed and routinely used by the British Geological Survey (BGS), with OpenQuake and EqHaz. In Section 2 we describe the similarities and differences between M3C, OpenQuake and EqHaz from a computational and methodological point of view. To compare them we use the source zone model of the south-east Canada (Atkinson & Goda, 2011) and UK (Musson & Sargeant, 2007). However, Section 3 describes only the source model in the eastern Canada in the interest of brevity. Section 4 shows the comparison of the three software packages in terms of the hazard results and computer performance. General conclusions are provided in Section 5.

2. Method

In the present work we test three software packages, i.e. M3C, OpenQuake, and EqHaz.

M3C was developed by Roger Musson in the second half of 1990s and nowadays is routinely used for seismic hazard assessment projects by the BGS (e.g. Musson, 1999, 2000, Musson & Sargeant, 2007; Musson, 2012). It is a method for a Monte Carlo based PSHA (see Figure 2 in Musson, 2000). After defining a source zone model, together with the recurrence statistics for each source zone, the code generates stochastic catalogues in N-years using Monte Carlo simulations (i.e. controlled random number generators). Each catalogue represents a version of what could occur based on past seismicity. The ground motion at a specific site is computed for each synthetic event. This process is iterated R-times in order to simulate millions of years of data. After sorting the results in order of decreasing severity, it is possible to identify ground motions associated with different probabilities of exceedance (Musson, 2000).

OpenQuake has been developed by the Global Earthquake Model initiative (Crowley et al., 2013). It is open-source software suitable for a large range of hazard applications and allows the user to make hazard as well risk calculations at variable scales, from single sites to large regions. In this work we test and analyze only the hazard module of OpenQuake. Assuming a source zone model, the software offers multiple types of hazard calculations: Cornell-McGuire PSHA as proposed by Field et al. (2003); a Monte Carlo based PSHA with a set of stochastic events and ground motion fields for each rupture; and DSHA for a single earthquake scenario (Pagani et al., 2014).

EqHaz is open-source software to perform a Monte Carlo based PSHA and, hence, it generates many synthetic catalogues based on a specific source zone model. It is designed to optimize the speed, flexibility, and ease of applicability for PSHA in stable continental regimes with a low-to-moderate seismicity, such as eastern North America (Assatourians & Atkinson, 2013).

From a computational point of view, M3C and EqHaz are very similar because they both are FORTRAN computer programs, the I/O format is ASCII, and they run on both Windows and Linux operating system using one processor (Table 1). The main difference between these two codes is that EqHaz is open-source, whereas M3C is available on request. The engine of OpenQuake is more complex because it consists of modules and separate routines, written in Python. The format of input/output information is a customized XML schema called Natural hazard Risk Markup Language (NRML) (see Pagani et al. (2014) and www.globalquakemodel.org/openquake/ for more details). Furthermore, this software runs only on Ubuntu system and uses as many processors as are available (Table 1).

From a methodological point of view, M3C and EqHaz perform a Monte Carlo based PSHA, as explained above. Although we tested OpenQuake also for a stochastic approach, we apply this software more extensively for Cornell-McGuire PSHA. There are two important differences between the three codes which influence mainly hazard calculations: 1) the GMPEs implementation; and 2) the modelling of finite ruptures (Table 2). In M3C and OpenQuake a large number of ground-motion models have been implemented in their own sub-routine. Therefore, it is possible to realize each model analytically without any rule-of-thumb conversion (Musson, 2009). In EqHaz the GMPEs are provided in a tabular format that includes median predictions as functions of magnitude, distance, frequency and epistemic uncertainty. This means the ground motion at site(s) is computed by a linear interpolation of the median motions provided by GMPE tables (Assatourians & Atkinson, 2013). This procedure makes it very difficult: 1) to use GMPEs with a complex functional form depending on other variables, such as focal depth, faulting style and depth to-top-of-rupture; and 2) to combine different ground-motion models in a weighted logic tree, highly recommended practice nowadays (e.g. Frankel et al., 2002; Bommer et al., 2005; Bommer & Akkar, 2010).

In OpenQuake synthetic finite-ruptures are modelled as planar rectangles in 3D space described by nodal plane orientation (i.e. strike, dip and rake), upper and lower depths of seismogenic zone, rupture aspect ratio, magnitude-area scaling relationship, and recurrence statistics, for both areal and fault sources (Pagani et al., 2014; Monelli et al, 2014). In M3C the same input parameters are used for generating synthetic finite-ruptures for fault source, but not for areal source where synthetic ruptures are defined by focal depth, faulting style, rake, strike, magnitude-length scaling relationship. Specifically, for an areal source a random epicenter, that is the center of the fault rupture, is generated. Then, rupture length is computed from the magnitude-length scaling relationship and the orientation is assigned based on the faulting style and the rake (Musson, 2009). In EqHaz the exact modelling of finite fault ruptures is not present because earthquakes are considered point process. Therefore, the source-to-site distance metrics is computed using empirical conversions allowing point source distances to be converted into finite rupture distances using equations derived for eastern North America (Atkinson & Goda, 2011; Assatourians & Atkinson, 2013). Their validity in other regions of the world has not tested yet. Furthermore, EqHaz uses the magnitude-length scaling relationship of Wells & Coppersmith (1994) for "all types of faults". In OpenQuake, instead, it is possible to choose between Wells & Coppersmith (1994) and Thomas et al. (2010) as magnitude-area scaling equation. M3C uses any magnitude-length scaling relationship because the parameters of the equation are provided as input parameters. Monelli et al. (2014) find that the use of a magnitude-area scaling relationship, rather than a magnitude-length scaling relationship justifies discrepancies in the hazard results.

A potential difference between M3C, OpenQuake, and EqHaz is how to handle epistemic uncertainty (e.g. uncertainty in the recurrence statistics, GMPEs, and source zone models) in the hazard analysis. In the Cornell-McGuire PSHA they are expressed by the logic-tree formalism where each branch is set up for alternative models, parameters and assumptions. Weights are given to each branch to reflect the relative confidence that the analyst has in that model. Then, the hazard results are computed for every possible combination of branches and the final outcome represents a weighted mean (e.g. McGuire, 2004; Musson, 2012). In a Monte Carlo based PSHA the aleatory uncertainties are expressed in terms of probability density functions and provided as input parameters. Although the two processes may be conceptually similar, the main difference between them is that in the Monte Carlo based PSHA, not all the branches are estimated, but they are sampled randomly and a single hazard calculation is performed (Musson, 2012).

The other potential differences between the three codes shown in Table 2 do not influence the hazard results if they are properly accounted in the input parameters. For example, to ensure similar results from the analyzed codes, the activity rate for each source zone must be computed for the same value of Mw (i.e. Mw=0).

3. Data

To compare the results produced by M3C, OpenQuake, and EqHaz, we use the source zone model of the south-eastern Canada (Montreal-Ottawa region). This region is characterized by a moderate seismicity with a limited understanding of tectonic features (Atkinson & Goda, 2011; www.seismotoolbox.ca/EQHAZ/). It consists of 17 areal sources and the most active source zone is the Iapetan rift (i.e. IRM) which Atkinson & Goda (2011) subdivide in nine sub-regions (Figure 1). Atkinson & Goda (2011) assume a range of permitted moment magnitude between 6.5 and 7.5 in IRM in agreement with the largest events occurred in similar tectonic regions worldwide (Adams & Basham, 1989; Johnston, 1989; Adams et al., 1995). The sub-regions included in IRM are characterized by a range of moment magnitude between 5 and 6.5 to avoid double-counting of seismic activity rates. The most recent 7 Mw earthquake has occurred in CHV1 in 1663; whereas, the location of the site is in MTL1. The recurrence parameters, i.e. activity rate and b-value, have been estimated by using the maximum likelihood method (Weichert, 1980; Atkinson & Goda, 2011). The double-truncated Gutenberg-Richter relationship requires a minimum magnitude (i.e. the magnitude of the smallest earthquakes to be considered of engineering significance) and a maximum magnitude that are shown in Table 3. The depth distribution of the model consists of three possible values, i.e. 5, 10 and 20, with assigned weights, i.e. 0.25, 0.50 and 0.25.
The GMPE included in the software EqHaz for the south-eastern Canada is an unpublished model documented by working notes (Atkinson, 2012). Therefore, the functional form and the coefficients of the model have not been published yet to be included in M3C and OpenQuake. Since we must use the same GMPE(s) to make a meaningful comparison between the three analyzed software packages, we have chosen to use the Boore & Atkinson (2008) model, updated in Atkinson & Boore (2011) for small magnitudes. It has a relatively simple functional form and, hence, it is straightforward to construct a table of the Boore & Atkinson (2008) GMPE and to implement it in EqHaz.

4. Results

In Section 2 we compared the software packages M3C (Musson, 1999, 2009), EqHaz (Assatourians & Atkinson, 2013) and OpenQuake (Pagani et al., 2014) in terms of methodology and computational aspects. In the present section we compare the hazard results, together with the computer performance, calculated by the three codes, using the source zone model of Section 3.
The source zone model of the south-eastern Canada was used to generate 1,000,000 synthetic catalogues of 100 years each using M3C. The length of the individual catalogues is largely immaterial; what matters is the total number of years, in this case, 100,000,000, which is sufficient to resolve the hazard accurately for a return period of 10,000 years (Musson, 2000). EqHaz instead generated 80,000 sub-catalogues of 100 years each. We calculated the hazard curves for peak-ground acceleration (PGA) and spectral acceleration at various periods in terms of annual probability of exceedance (first column of Figure 2). To make a quantitative evaluation of the discrepancy between the curves, we estimate the percentage of the difference between pairs of annual probability of exceedance, defined by Monelli et al. (2014) (second column of Figure 2).
As shown by the plots in Figure 2, the hazard curves produced by M3C and OpenQuake are more similar than those between M3C/OpenQuake and EqHaz. This is confirmed by the values assumed by Δ(M3C-OQ) that are lower than 10%; whereas, Δ(M3C-EqHaz) and Δ(OQ-EqHaz) are higher, between 10 and 100%. Although the annual probability of exceedance is plotted down to 10^{-6}, its range of interest in earthquake engineering is 10^{-5} to 10^{-2} (McGuire, 2004). Therefore, the discrepancy in the hazard curves for large PGA is not significant. We apply also the OpenQuake software for Monte Carlo based PSHA, generating an increasing number of stochastic events (not shown here). As expected, by increasing the

number of synthetic earthquakes, the hazard curves become identical to that computed by M3C.

We computed PGA hazard maps with a return period of 475 years in the eastern Canada using M3C, OpenQuake, and EqHaz (first column in Figure 3). Although they appear relatively similar to each other, we quantified possible discrepancies by computing the percentage of difference between pairs of maps (second column in Figure 3). Maps of M3C and EqHaz are characterized by a grid spacing of 0.265°; whereas, maps from OpenQuake have a grid spacing of 24.5 km. The slightly different way of meshing the study area influences the computation of Δ. Nevertheless, it is clear that M3C and OpenQuake provide more similar results than EqHaz and the largest values of Δ are at the edge of the study area.

Concerning computer performance, we used one processor to run M3C and EqHaz. M3C takes ~6 minutes for generating 1,000,000 synthetic models, and EqHaz, ~11 hours for generating 80,000 sub-catalogues in each of the 17 source zones. OpenQuakes takes ~15 minutes for performing the Cornell-McGuire PSHA, and ~33 hours for simulating 10,000 stochastic events for a Monte Carlo based PSHA. In both cases four processors were used.

5. Summary & Conclusions

The present work aimed to compare the most recent software packages with the approach used in BGS and encoded in the FORTRAN programme M3C. Although in the last years many codes have been published, we have decided to compare M3C with OpenQuake and EqHaz for the following reasons: EqHaz appeared to have a very similar engine with M3C; OpenQuake has a wide resonance in the hazard community and an increasing number of analysts are using this software for SHA. We analysed the methodology and the computational aspects of the three codes (Section 2) and, then, we run them using the source zone model of the south-eastern Canada (Section 3). For the brevity of the paper, we showed hazard curves and maps computed by the software packages and we made a quantitative evaluation of the discrepancies between the results (Section 4).

We have found that M3C and OpenQuake provide very similar hazard results. This confirms that if input parameters are identical, outputs from any software packages have an excellent agreement. The discrepancies between M3C/OpenQuake and EqHaz are mainly due to characteristics of the engine of EqHaz, i.e. tabular format of GMPEs and the lack of fault rupture modelling. This is explained by the fact that EqHaz is a code built for PSHA in stable continental regimes, such as the central and eastern North America, and is less flexible to be adapted to other tectonic regimes. It is worth noting that M3C is the fastest code, but OpenQuake includes multiple hazard calculators in its engine.

Table 1: Comparison of M3C, OpenQuake, and EqHaz in terms of computational engine.

	M3C	**OpenQuake**	**EqHaz**
Code availability	On request	Open-source, www.globalquakemodel.org/openquake	Open-source, www.seismotoolbox.ca/EQHAZ
Language	FORTRAN	Python	FORTRAN
I/O format	ASCII	NRML	ASCII
Operating system	Windows and Linux	Ubuntu	Windows and Linux
Number of processors	Single processor	As many processors as available	Single processor

Table 2: Comparison of M3C, OpenQuake, and EqHaz in terms of methodology.

	M3C	**OpenQuake**	**EqHaz**
Method for PSHA	Monte Carlo based PSHA	DSHA, Cornell-McGuire PSHA, Monte Carlo based PSHA	Monte Carlo based PSHA

How to generate synthetic catalogues	Generate R catalogues in N-years within the study area	Generate R catalogues in N-years within the study area for Monte Carlo based PSHA	Generate R sub-catalogues in N-years in each source zone
Gutenberg-Richter relationship	Any form, included double-truncated	Any form, included double-truncated	Any form, included double-truncated
Activity rate	Computed for Mw=0 and ≠0	Computed for Mw=0	Computed for Mw=0
Earthquake rupture modeling	Precise for fault sources	Rupture finiteness for fault and areal sources	Not present
Magnitude-scaling relationship for fault ruptures	Any magnitude-length scaling relationship provided in the input file	Magnitude-length scaling relationship of Wells & Coppersmith (1994) and Thomas et al. (2010)	Magnitude-length scaling relationship of Wells & Coppersmith (1994) for "all types of faults"
GMPE implementation	Many GMPEs implemented in their own sub-routine	Many GMPEs implemented in their own sub-routine	Tabular format where median predictions are functions of Mw, distance, frequency and epistemic uncertainties

Table 3: Lower an upper bound of moment magnitude for the Gutenberg-Richter relationship for each source zone of the eastern Canada.

	Mmin	**Mmax**
BG3	5.0	7.0
BG2	5.0	7.0
BG1	5.0	7.0
IRM	6.5	7.5
TIM1	5.0	6.5
WQC1	5.0	7.0
APP	5.0	7.0
NB	5.0	7.0
FUND	5.0	7.0
SAG1	5.0	6.5
QC1	5.0	6.5
OTTV	5.0	6.5
MTL1	5.0	6.5
LSH1	5.0	6.5
LSL1	5.0	6.5
3RIV	5.0	6.5
CHV1	5.0	6.5

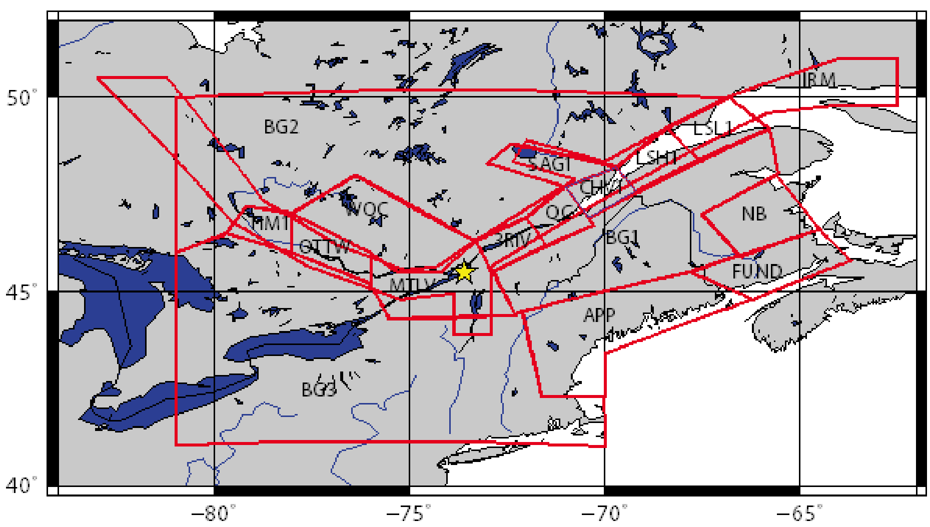

Figure 1. Source zone model of the south-eastern Canada from Atkinson & Goda (2011) consisting of 17 zones. The site is indicated by a yellow star.

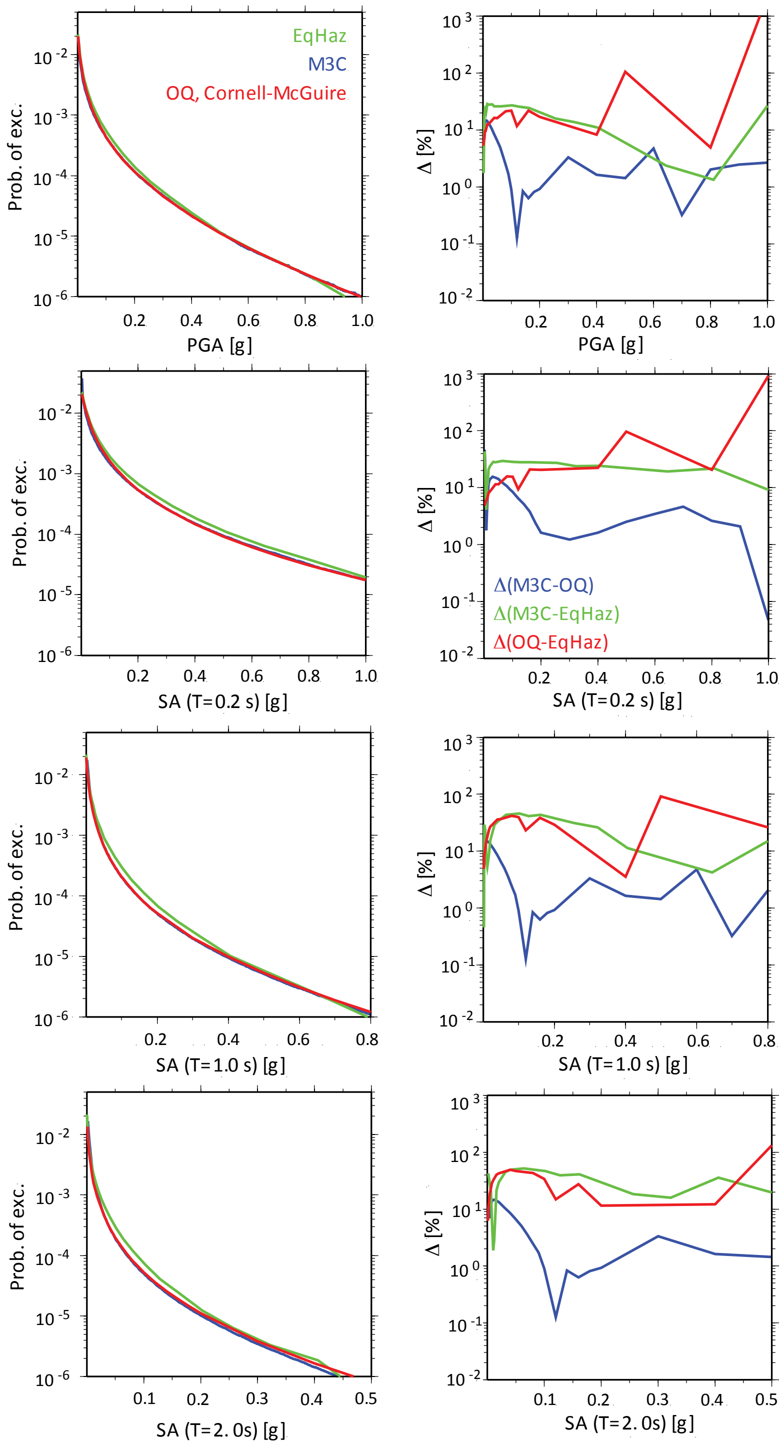

Figure 2. In the first column, hazard curves for PGA and spectral acceleration at a period of 0.2, 1.0, and 2.0 s for the source model of the Eastern Canada at a specific site, and in the second column, percentage of difference between pairs of curves. M3C and EqHaz were run for Monte Carlo based PSHA, whereas OpenQuake, for Cornell-McGuire PSHA.

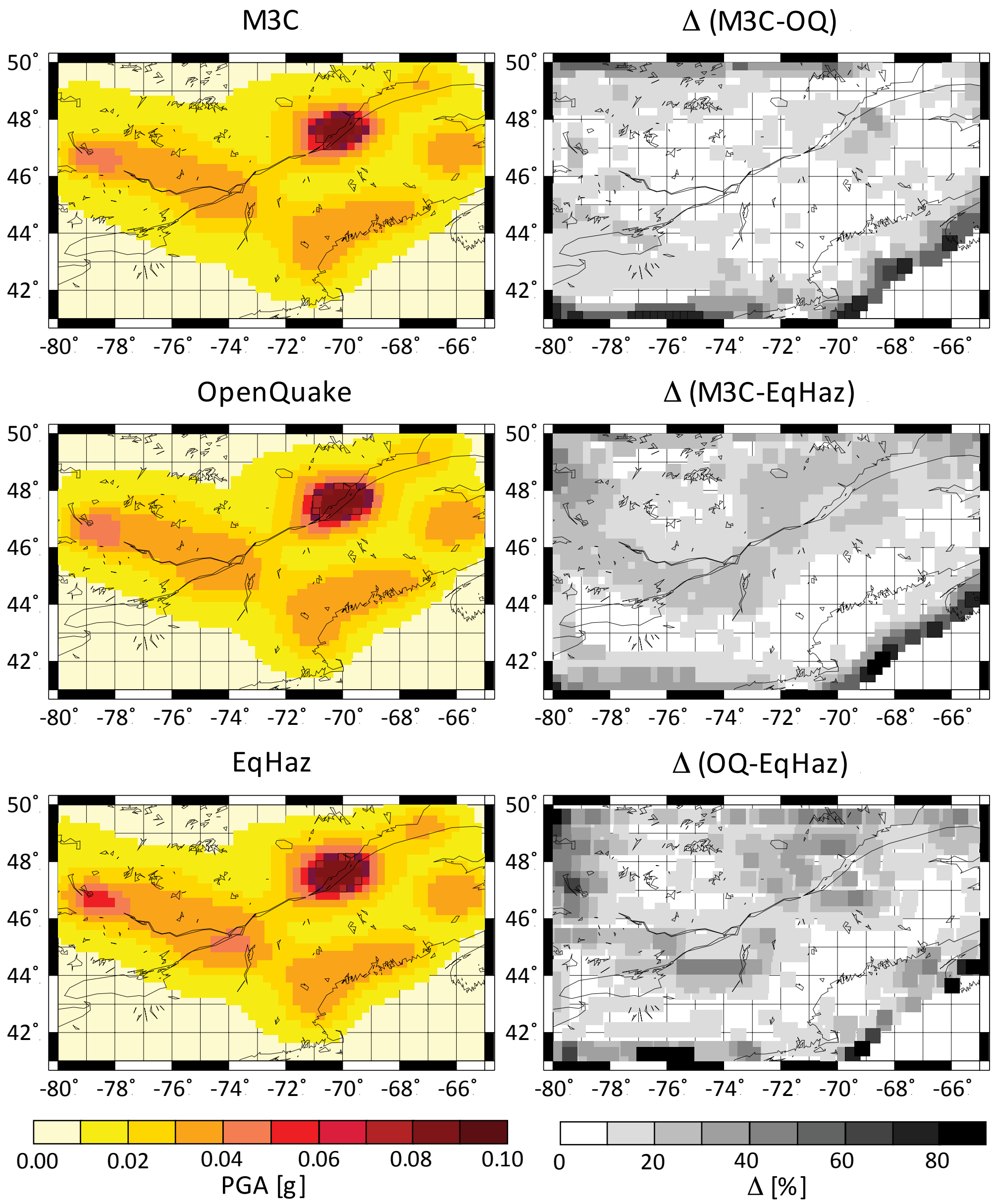

Figure 3. PGA hazard maps with a return period of 475 in the Eastern Canada in the first column, and percentage of the difference between pairs of maps on the second column.

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