Pagani, M., Garcia-Pelaez, J., Gee, R., Johnson, K., Poggi, V., Silva, V., Simionato, M., Styron, R., Viganò, D., Danciu, L., Monelli, D., Weatherill, G. (2020): The 2018 version of the Global Earthquake Model: Hazard component. - Earthquake Spectra, 36, 1, suppl., 226-251.

https://doi.org/10.1177/8755293020931866

The 2018 version of the Global Earthquake Model: Hazard component

Marco Pagani[1], Julio Garcia-Pelaez[1], Robin Gee, M.EERI[1], Kendra Johnson[1], Valerio Poggi[1,2],
Vitor Silva, M.EERI[3], Michele Simionato[4], Richard Styron[1], Daniele Viganò[1], Laurentiu Danciu[5],
Damiano Monelli[6], and GraemeWeatherill[7]

Abstract

In December 2018, at the conclusion of its second implementation phase, the Global Earthquake Model (GEM) Foundation released its first version of a map outlining the spatial distribution of seismic hazard at a global scale. The map is the result of an extensive, joint effort combining the results obtained from a collection of probabilistic seismic hazard models, called the GEM Mosaic. Together, the map and the underlying database of models provide an up-to-date view of the earthquake threat globally. In addition, using the Mosaic, a synopsis of the current state-of-practice in modeling probabilistic seismic hazard at national and regional scales is possible. The process adopted for the compilation of the Mosaic adhered to the maximum extent possible to GEM's principles of collaboration, inclusiveness, transparency, and reproducibility. For each region, priority was given to seismic hazard models either developed by well-recognized national agencies or by large collaborative projects involving local scientists. The version of the GEM Mosaic presented herein contains 30 probabilistic seismic hazard models, 14 of which represent national or sub-national models; the remainder are regional-scale models. We discuss the general qualities of these models, the underlying framework of the database, and the outlook for the Mosaic's utility and its future versions.

Keywords

Seismic hazard, PSHA, GEM, Global Earthquake Model, OpenQuake

Introduction

Seismic hazard maps depict the geographic distribution of shaking intensity with a given annual frequency (or probability) of exceedance and are used to portray the results of seismic hazard analyses. Hazard analyses are commonly classified based on the spatial extent of the area covered by the analysis. Typical scales of investigation include site-specific studies, urban seismic microzonations, and national, regional, and global hazard analyses. Very often, hazard maps are built at a national scale, as this information forms the basis for defining building design actions. These large-scale investigations, as opposed to the ones performed at urban and site scales, usually do not incorporate site conditions and instead provide hazard on a reference site, commonly the engineering bedrock (e.g. Vs30 > 800 m/s) or stiff soil. Global seismic hazard maps, such as the map presented here, inform specialists and the general public about the most seismically dangerous regions of the world.

Two approaches are available for constructing a global seismic hazard model. The first one involves subdividing inland territories into a number of areas and constructing independent hazard

---

[1] Hazard Team, Global Earthquake Model (GEM) Foundation, Pavia, Italy
[2] National Institute of Oceanography and Applied Geophysics, OGS, Italy
[3] Risk Team, Global Earthquake Model (GEM) Foundation, Pavia, Italy
[4] IT Team, Global Earthquake Model (GEM) Foundation, Pavia, Italy
[5] Swiss Seismological Service, ETH Zurich, Zurich, Switzerland
[6] Renaissance Re, Zurich, Switzerland
[7] GFZ German Research Centre for Geosciences, Potsdam, Germany

Corresponding author:
Marco Pagani, Hazard Team, Global Earthquake Model (GEM) Foundation, Via Ferrata 1, 27100 Pavia, Italy.
Email: marco.pagani@globalquakemodel.org

models for each of them, achieving global coverage using a "mosaic" of models. This approach was used to construct the well-known Global Seismic Hazard Assessment Program (GSHAP) model (Giardini et al., 1999), in which ten principal regional models were combined with additional models covering specific areas, for example, the PILOTO project for the Northern Andes (Dimaté et al., 1999) or the CAUCAS project in the Caucasus region (Balassanian et al., 1999). The second approach tackles the problem more radically by building a single seismic hazard model using fewer, but more homogeneous, methods and data sets with global coverage (e.g. a global earthquake catalog, a global database of active faults). This approach was used, for example, by Weatherill and Pagani (2014) to explore the feasibility of a uniform approach to global hazard modeling and by Ordaz et al. (2014) to support the risk calculation within the 2013 version of the Global Assessment Report on Disaster Risk Reduction (GAR).

Both strategies present advantages and disadvantages. The first procedure is more open to collaboration and incorporation of existing seismic hazard models developed at national or regional scales. It does not inherently guarantee homogeneity, since the methodologies used to construct each model will probably be different, and the basic data sets are likely compiled following different criteria meaning that they may exhibit different levels of completeness. For this reason, the GSHAP project held several regional meetings to ensure that the various hazard models were implemented in agreement with the technical guidelines described in Basham and Giardini (1993). The second approach streamlines construction of a hazard input model with exclusive methodologies and data sets and, therefore, presumably results in a more homogeneous model. This approach limits the role and contributions of the earthquake hazard community, and still does not necessarily guarantee homogeneity, since global data sets may not have spatially constant quality, and the adequacy of each modeling approach varies depending on the available information and the tectonic context.

During its first implementation phase, which began in 2009 and concluded in 2014, Global Earthquake Model (GEM) collaborated with various initiatives at regional levels (e.g. Şeşetyan et al., 2018; Ullah et al., 2015; Woessner et al., 2015) and worked at constructing the key ingredients for developing a modern version of a global hazard and risk model (Pagani et al., 2015). These key ingredients included basic data sets such as a global instrumental catalog (Storchak et al., 2013), a global uniform macroseismic earthquake catalog (Albini et al., 2014), a global strain rate model (Kreemer et al., 2014), a global database of active faults (Christophersen et al., 2015), guidelines for modeling ground motions (Stewart et al., 2013), and a computational engine (Pagani et al., 2014).

In December 2018, at the culmination of its second implementation phase (2015-2018), GEM completed the first version of the Global Earthquake Model, releasing a global seismic hazard map (Pagani et al., 2018), as described herein, and a global exposure database and global risk map described by Silva et al. (2020). This map and the underlying hazard model result from the combination of 30 regional and national probabilistic seismic hazard models - mostly developed within the last ten years - using the mosaic approach (the GEM hazard mosaic). Supplementing the hazard results obtained within GEM's second implementation phase, a global homogenized instrumental earthquake catalog (Weatherill et al., 2016) and a Global Active Fault Database (GAF-DB; Styron and Pagani, 2020) were produced. The latter in particular expands on the work undertaken within the Faulted Earth project (Christophersen et al., 2015) as well as in regional databases created in the framework of GEM projects (e.g. South America, Caribbean and Central America). These products, along with the results of the global projects completed by GEM during its first implementation phase (Pagani et al., 2015), were key for developing hazard models in areas where GEM was unable to form collaborations with local institutions.

This article provides an introduction to the GEM hazard mosaic (the Mosaic herein -see also http://www.globalquakemodel.org/gem) and is complemented by contributions that elaborate on some of the individual hazard models developed as a part of this effort, as described in the rest of the article, and the corresponding risk models that emerged alongside the Mosaic (Silva et al., 2020, and references therein). Here, we describe the motivations for compiling the Mosaic and explain how these incentives helped to construct the underlying framework, including the criteria used to select models. We demonstrate the framework on the first version of the Mosaic, discussing the main characteristics of the included models. We present a global map of seismic hazard, using mean peak ground acceleration (PGA) on rock as a representative intensity measure, and explain the procedure used to prepare the global map, including the harmonization of results across model borders. We compare properties of the computed global hazard map to those of previously released models. Finally, we discuss the utility of the Mosaic to the scientific community, and discuss the outlook for future updates to the Mosaic components.

The criteria used to compile the GEM hazard mosaic

The criteria used to compile the underlying models of the Mosaic were defined based on the motivations for this effort and its anticipated utility. The simplified motivation for the Mosaic was to provide the scientific community with a suite of seismic hazard model inputs with a uniform format that together achieve global coverage. More profoundly, the compilation should represent the state of practice of probabilistic seismic hazard analysis (PSHA), addressing, for example, the following questions: What standards are applied to the data sets used to characterize seismic sources? What seismic source typologies and assumptions have become commonplace in the different tectonic contexts? How is uncertainty captured in ground motion and source models? The answers may reveal geographic discrepancies, showing variability in the collective understanding and representation of seismic hazard across the globe. For example, regions and nations with long-standing geophysical agencies - and especially those with an apparent earthquake threat - may incorporate unique tectonic regionalization schematics and source types; calibrate regional ground motion models (GMMs) based on years of strong-motion recordings; or develop complex logic trees that capture the range of probable parameters for both the seismic source model (SSM) and GMM components. On the contrary, the models for other regions may be fully dependent on global data sets.

A key aspect of any global seismic hazard model is its compilation in a uniform format compatible with a single calculation engine. For the Mosaic, this is the OpenQuake Engine (Pagani et al., 2014) - the open-source hazard and risk calculation engine developed by the GEM Foundation. As seismic hazard models were incorporated into the Mosaic, the OpenQuake Engine simultaneously underwent necessary developments to support the diversity of source types and modeling approaches found within these models. Thus, a second motivation for compiling the Mosaic is to support the OpenQuake Engine's evolution in tandem with progress in the field of seismic hazard analysis, providing the scientific community with a calculation engine that is compatible with the most current research and modeling practices.

Given the commitment to achieve our first global coverage by the end of 2018, we compiled the Mosaic following selection criteria with a balance between pragmatism and GEM's principles of collaboration, openness, and transparency, using to the greatest extent possible hazard models developed by local communities of scientists. "Openness" in this context means public accessibility of data sets and products, and underpins a third motivation for the Mosaic: to exemplify and promote the development of hazard models that can be shared among the interested communities (scientific and otherwise). To this end, the models selected for the Mosaic were preferentially accompanied by bilateral agreements between GEM and the original model developers allowing for their models to be shared.

In order to achieve this goal efficiently while maintaining focus on the aforementioned motivations, we selected a model for each region using a three-tier approach (see Table 1 and Figure 1). Note that the assignment of a model to a tier is based on its origin and does not imply an indication of its quality. Tier 1 includes models developed by either an internationally recognized national agency, or a cooperative scientific project involving several organizations. Models in this tier generally rely on the broadest involvement of the local scientific community and incorporate high scientific and technical standards, representing what we consider the ideal case. The selected Tier 1 models include several national models, such as the 2014 United States Geological Survey (USGS) national seismic hazard model for Conterminous US (Petersen et al., 2014), the national seismic hazard model for Japan (Headquarters for Earthquake Research Promotion (HERP), 2014), the 2015 version of the Canada national hazard model (Adams et al., 2015), the 2017 version of the Indonesia national model (Irsyam et al., Submitted), and the 2018 version of the Australia national model (Allen et al., 2020a). Many of the regional models are also Tier 1, including the ESHM13 model in Europe (Woessner et al., 2015), the Earthquake Model of Central Asia (Ullah et al., 2015), and the EMME (Earthquake Model for the Middle East) model in the Middle East (Şeşetyan et al., 2018), each created by an associated project, and the South America Risk Assessment (SARA) project in South America (supported by the Swiss Re Foundation) and the Caribbean and Central America Risk Analysis (CCARA) project in Central America and the Caribbean (supported by the United States Agency for International Development (USAID)), which were constructed during projects carried out in collaboration with partner organizations.

In areas where Tier 1 models are not available, we applied the second selection criterion, searching for models published in the literature (Tier 2) with sufficient detail to implement into the OpenQuake Engine. The model for India and its surroundings belongs to this tier. Where this was not possible, GEM developed its own seismic hazard models for the remaining uncovered areas (Tier 3), either by partnering with another organization, or led solely by hazard modelers working within the GEM Secretariat. Due to the timeline put forth for completing the first version of the Mosaic, at the time of writing, peer-reviewed documentation has not yet been published for all Tier 3 models. In these cases, we refer the reader to the GEM Hazard Model Documentation (see Table 1). Relevant publication references will be posted here as they become available.

While the Tier 1 models included in this version of the Mosaic, and in particular those covering large geographic areas, were mostly released during the last decade, there are some areas where more recent national models exist. However, in compiling the first version of the Mosaic, we sometimes gave precedence to regional models over national models. For example, we chose regional models that cover contiguous land masses rather than national models for smaller countries, as long as the regional model was also Tier 1.

The hazard inputs for all models included in the Mosaic use the standard format of the OpenQuake Engine. Each hazard input model comprises a seismic source characterization (SSC) accounting for all seismicity of interest and the associated epistemic uncertainties, and a ground motion characterization (GMC) that describes the GMMs used to compute hazard results. The SSC is further divisible into two components. The first is at least one seismic source model (SSM) which is a list of sources that account for all possible seismicity of engineering importance in the proximity of the investigated area; individual sources in an SSM only consider aleatory uncertainty. The second component is a logic tree describing epistemic uncertainty in the SSC. The logic tree can be used to weight the available SSMs and also to specify the probable alternative parameters for sources in the SSMs. The GMC is also described by a logic tree, which consists of weighted GMMs for each tectonic region.

For the models included in the Mosaic that were not originally implemented in the OpenQuake Engine, we developed codes to automatically convert the original models to the OpenQuake Engine format. Translating a hazard model from one software format to another often requires modeling decisions that attempt to replicate concepts inherent to the original software; this is possible because of the OpenQuake Engine's flexible framework that allows the user an extensive degree of control over the internal mechanics of the PSHA calculation. We followed this approach to incorporate various models with unique properties produced by the USGS, as well as the national hazard model for Japan, for example. In parallel with the translation of hazard models, we performed validations between the original results (e.g. hazard curves and maps) and those obtained using the OpenQuake Engine.

Table 1. Components of the GEM hazard mosaic

Acr.	Year	Region covered	Tier	LT-GMM	LT-SSM	Faults	Unique GMPEs	Project	OQ	Reference publications
ALS	2007	Alaska	1	X	X	X	8			Wesson et al. (2007, 2008)
ARB	2018	Arabian Peninsula	1	X	X		17			Zahran et al. (2015, 2016)
AUS	2018	Australia	1	X	X	X	20		X	Allen et al. (2020a)
CAN	2015	Canada	1	X	X	X	21			Adams et al. (2015)
CCA	2018	Caribbean, Central America	1	X				CCARA		
CEA	2018	Central Asia	1	X			4	EMCA	X	Ullah et al. (2015)
CHN	2015	China	1				4			Gao (2015)
EUR	2013	Europe	1	X	X	X	20	SHARE	X	Woessner et al. (2015)
HAW	1998	Hawaii	1	X		X	5			Klein et al. (2001)
IDN	2017	Indonesia	1	X		X	13		/	Irsyam et al. (Submitted)
IND	2012	India and surroundings	2	X	X		24			Nath and Thingbaijam (2012)
JPN	2014	Japan	1			X	5			HERP (2014)
KOR	2018	Korean Peninsula	3	X		X	11			Gao (2015), HERP (2014)
MEX	2018	Mexico	3	X		X	14		X	
MIE	2016	Middle East	1	X	X	X	15	EMME	X	Danciu et al. (2018a, 2018b), Şeşetyan et al. (2018)
NAF	2018	Northern Africa	3	X	X	X	4		X	Poggi et al. (2020)
NEA	2018	Northeastern Asia	3	X		X	9		X	
NWA	2018	Northeastern Europe, Northwestern Asia	3	X			5		X	
NZL	2010	New Zealand	1			X	4		X	Stirling et al. (2012)
PHL	2018	Philippines	3	X		X	13		X	Pen˜arubia et al. (2020)
PAC	2018	Pacific Islands	3	X		X	9		X	Johnson et al. (Submitted)
PNG	2015	Papua New Guinea	1	X	X	X	9		X	Ghasemi et al. (2016)
SAM	2018	South America	1	X		X	14	SARA	X	
SEA	2018	Southeast Asia	1	X	X	X	11		X	Ornthammarath et al. (Submitted)
SSA	2018	Sub-Saharan Africa	1	X	X		4	SSAHARA	X	Poggi et al. (2017)
TEM	2015	Taiwan	1			X	3		X	Wang et al. (2016)

(continued)

Table 1. Continued

Acr.	Year	Region covered	Tier	LT-GMM	LT-SSM	Faults	Unique GMPEs	Project	OQ	Reference publications
UCF	2014	California	1	X	X	X	15			Field et al. (2014)
USA	2014	Conterminous U.S.	1	X	X	X	23			Petersen et al. (2015)
WAF	2018	Western Africa	3	X	X		2		X	
ZAF	2018	South Africa	1	X	X	X	2		X	Midzi et al. (2019)

GEM: Global Earthquake Model; CCARA: Caribbean and Central America Risk Analysis; EMCA: Earthquake Model for Central Asia; EMME: Earthquake Model for the Middle East;

SARA: South America Risk Assessment; SSAHARA: Sub-Saharan Africa Hazard and Risk Assessment; LT-GMM: Logic tree for Ground-Motion Modelling; LT-SSM: Logic tree for Seismic Source Modelling; GMPE: Ground-Motion Prediction Equation.

The column values provide a broad overview of the qualities of the models included in the first Mosaic version. **LT-GMM** and **LT-SSM** are epistemic uncertainty in the ground motion model and seismic source model, respectively. Note that these columns are binary, and the extent to which epistemic uncertainty is modeled varies among the models; for example, models may use weighted GMPEs for only one tectonic region, or consider the uncertainty of just a single source parameter (e.g. maximum magnitude). **Faults** is marked for models that include any typology of fault source (simple, complex, or predefined rupture geometries). **Unique GMPE**s is the total number of GMPEs used by the model, regardless of the tectonic region type; sometimes, a GMPE is used for more than one tectonic region. If **OQ** is marked, the model was originally implemented in the OpenQuake Engine. Indonesia is partially marked, since the original implementation included two calculation engines. NB: The column values that correspond to model qualities reflect the models included in version 2018.1 of the Mosaic, and that at the time of publication, some models have already undergone updates. Namely, the reference for PHL (Peñarubia et al., 2020) reflects an updated model; see detail in text. For Tier 3 models without references and the CCARA and SARA projects, please refer to the GEM Hazard Model Documentation (https://hazard.openquake.org/gem/) for a description of the modeling methods and details. Publications will be posted on the individual model pages as they become available.

Having the whole suite of models represented with a common format offers several advantages. First, a global hazard map or similar product is more easily computed from a suite of models that all comply with a standard format. Second, the common format offers a simplified utility to users of the Mosaic and the OpenQuake Engine format in particular ensures that the models can be easily used with the OpenQuake Engine (Pagani et al., 2014). Future updates and additions to the GEM hazard mosaic will continue to follow this formatting standard.

The components of the Mosaic and their general characteristics

The oldest model included in the Mosaic is the USGS Hawaii model (Klein et al., 2001); all others were published after 2007. Overall, the Mosaic assembles about 3.5 million earthquake sources that together generate around 1.8 billion ruptures, each of which contributes to the final seismic hazard. The GMC includes about 90 ground motion prediction equations (GMPEs) subdivided into various tectonic regions (e.g. Active Shallow Crust, Stable Continental Crust). The 30 selected hazard models can be used to compute the hazard produced by earthquakes of tectonic origin; the only exception is the South Africa national model which also accounts for seismicity of mining origin (Midzi et al., 2020).

Here, we describe each of the models included in the Mosaic, covering the globe by geographic region. Rather than providing a homogeneous description of the various models, we highlight the characteristics that make the respective model novel or unique, or that categorize it methodologically (or otherwise) with some of the other included models. Table 1 lists the most general characteristics of the models: the model tier, the types of epistemic uncertainty included, whether any fault sources are used, and the number of unique GMPEs used.

North America

We discuss coverage of North America in five regions: Alaska, Canada, the contiguous United States, Mexico, and Central America and the Caribbean. The hazard input model for Alaska (Wesson et al., 2007, 2008) is based on the typical framework used by the USGS for the construction of seismic hazard analyses, both within the United States as well as for territories overseas. Shallow seismicity is accounted for by a combination of smoothed seismicity and fault sources, while subduction earthquakes are separated into interface earthquakes generated by fault sources with a three-dimensional (3D) geometry, and intraslab earthquakes organized as layers of point sources obtained by smoothing hypocentral depth-based classes of intraslab seismicity.

The model for Canada is the 5th Generation national hazard model created by Natural Resources Canada (Adams et al., 2015). Compared to the previous version, it contains several improvements including a probabilistic computation of hazard generated by the Cascadia subduction zone, which had been treated deterministically in previous models. The SSC is organized into four quadrants: two covering the eastern and western Arctic regions, one covering British Columbia and part of the West, and one covering Ontario, Quebec, and Atlantic Canada. The 2015 Canada model is, to our knowledge, the first national hazard model accounting for GMM epistemic uncertainty via a suite of referenced backbone GMMs (Allen et al., 2020b; Atkinson and Adams, 2013).

The 2014 USGS National Seismic Hazard Model for the Conterminous United States utilized in the Mosaic includes two hazard models. The Uniform California Earthquake rupture forecast, version 3 (UCERF3) model (Field et al., 2014) covers California, while a more conventional model is used to compute hazard for all the other states (Petersen et al., 2014). Hazard calculation with these two models required the implementation of additional features in the OpenQuake Engine such as a specific calculator for the UCERF3 model. The implementation of the UCERF3 model and its specific calculator was particularly challenging because the SSM has a unique structure, which (Field et al., 2014) enables rupture configurations that could not otherwise be realized from common source parameters (e.g. hypocenters, geometries, and rates), such as discontinuous multi-fault ruptures with individually calibrated probabilities.

The model for Mexico was created by the GEM Hazard Team. The SSC includes 3D fault sources modeling shallow seismicity and subduction interface earthquakes, point sources accounting for shallow distributed seismicity in active and stable crust, and 3D ruptures constrained within the volume of the slab accounting for the deep subduction seismicity. The crustal faults are modified from the catalog by Villegas et al. (2017). The GMC is based on residual analysis using strong ground motion data and a set of candidate GMMs. The strong-motion data were provided by the National Autonomous University of Mexico (UNAM, http://www.ssn.unam.mx/) and the Center for Scientific Research and Higher Education at Ensenada (CICESE, http://resnom.cicese.mx/).

The core of the model for the Caribbean and Central America was developed within the CCARA project, with additions that cover Cuba and Puerto Rico. The structure of the hazard input model resembles that of the Mexico model. It includes three major subduction zones: the Middle American subduction system, extending along the Pacific coast from Panama to southern Mexico; the eastern Caribbean (Lesser Antilles) subduction system; and the Puerto Rico-Hispaniola subduction system, proximal to the northeastern corner of the Caribbean Plate. An active fault database (Styron et al., 2020) was developed for the CCARA project, which was the first active fault dataset mapped by GEM for the GAF-DB; this regional database served as the template for the global database (Styron et al., 2018a). The GMC is based on residual analysis using strong ground motion data covering both the Caribbean and Central America and a set of candidate GMMs. Data from the Lesser Antilles were retrieved from the Engineering Strong-Motion database (ESM, https://esm.mi.ingv.it), while the Ministerio de Medio Ambiente y Recursos Naturales (MARN, http://www.marn.gob.sv/) provided the recordings for El Salvador through a bilateral collaboration with GEM.

South America

In South America, the SSC consists of a single SSM originally created for the SARA project (Garcia et al., 2017) and subsequently updated by the GEM Hazard Team. The structure of the hazard input model resembles that of the Mexico and Caribbean and Central America models, but here earthquake rates on the subduction interface also consider a tectonic component derived from fault area, seismic coupling, and plate convergence rate (Pagani et al., 2020). In most of this region, hazard is dominated by the subduction sources located along the western coast of the continent. Local shallow faults control hazard peaks throughout the Andean cordillera and foreland. The GMC (Drouet et al., 2017) is based on extensive residual analysis using a database of strong-motion recordings covering Colombia, Ecuador, Chile, and Brazil. The pattern of hazard computed is generally consistent with the one described by Petersen et al. (2018) with peaks of hazard concentrated in the central part of Chile and in Ecuador.

Europe and Africa

The ESHM13 Model (Woessner et al., 2015) developed within the SHARE project (Giardini et al., 2014) was selected for calculating seismic hazard in Europe. Funded by the European Union under the Seventh Framework Program (FP7), Seismic Hazard Harmonisation in Europe (SHARE) was the earliest regional project to produce a model included herein and was a collaboration that paved the way for the construction of similar models in other areas. This model was also an important test case in the early development of the OpenQuake Engine, as it was used to challenge the software capability to compute hazard at a continental scale. The ESHM13 SSC is composed of three SSMs developed with different initial data sets and modeling strategies, described in detail by Woessner et al. (2015). The first and most traditional model was obtained by harmonizing the geometries of area sources defined in published national hazard models. The second model represented a novelty for Europe, as it used fault sources extensively for hazard calculation, particularly in the active and extended shallow crust regions. The third model was a smoothed seismicity model obtained with the application of a new method proposed by Hiemer et al. (2014).

The model for Northern Africa (Poggi et al., 2020) was built by the GEM Hazard Team using an earthquake catalog covering the entire region and a new database of shallow active faults (Styron and Poggi, 2018) compiled as part of the construction of the GAF-DB. The SSC consists of two SSMs: one which includes both smoothed seismicity and fault sources, and a second containing only smoothed seismicity, but using different smoothing lengths than the former SSM, and considering epistemic uncertainty of seismicity rates.

The model covering the East African Rift system is the latest evolution of work originally performed within the GEM-AfricaArray collaboration in the context of the Sub- Saharan Africa Hazard and Risk Assessment (SSAHARA; Poggi et al., 2017). The SSM includes smoothed seismicity within source zones aligned parallel to the Rift Valley axis, starting from the Gulf of Aden until Zimbabwe where the rift splays into a number of minor tectonic structures. The GMC, which is particularly uncertain in this region - and more generally in Africa - given the complete absence of strong-motion recordings, includes transition zones between purely active shallow crust and a stable continental region, weighting models that are normally assigned to the two unique tectonic regions.

The model for Western Africa covers an area entirely classified as stable crust (see, for example, Chen et al., 2018). It was developed by the GEM Hazard Team primarily using the globally available data sets and information taken from literature. One of the most prominent earthquake sources in this model, located in southern Ghana, is attributed to fault structures bounding the southeast margin of the West Africa Craton and the continental margin (e.g. Ahulu et al., 2018; Amponsah, 2004); seismicity data in this region were partly supplemented by Amponsah et al. (2012). The SSC uses a single SSM with smoothed seismicity and considers epistemic uncertainty in earthquake rates and maximum magnitudes.

South Africa is covered by the model of Midzi et al. (2019), which was produced by a collaboration between the Council of Geoscience in South Africa and the Indian Institute of Technology, Jammu. The SSM contains both faults and area sources, and because of the low level of seismicity and limited data, the authors defined the SSC to incorporate alternative Gutenberg-Richter, maximum magnitude, and depth values to account for epistemic uncertainty (discussed more in the section “A summary of the main characteristics of models in the Mosaic”).

Asia

Asia is the most complex continent in terms of both the number of hazard models included in the Mosaic and their seismotectonic diversity. We describe the main characteristics of the 13 chosen models going from West to East.

The westernmost coverage of Asia is the EMME (Şeşetyan et al., 2018), which extends from the western coast of Turkey to Afghanistan and Pakistan, including the Caucasian countries (except Russia), Iraq, and countries in the Middle East that border the Mediterranean Sea. The EMME model was created by a large group of local scientists, and represented an important achievement with respect to seismic hazard assessment in the region. The project also facilitated the compilation of new basic data sets, including an earthquake catalog (Zare et al., 2014), an active fault database (Danciu et al., 2018b), and a strong-motion database (Danciu et al., 2018a). The SSC includes two SSMs (Danciu et al., 2018b). The first uses fault sources to model the Makran subduction interface and other crustal faults; area sources to account for intraslab and deep seismicity; and smoothed, gridded point sources elsewhere. The second SSM uses area sources to cover all tectonic regions.

The model for the Arabian Peninsula (Zahran et al., 2015, 2016) was developed by the Saudi Geological Survey (SGS). The SSC includes two SSMs that comprise area sources with identical geometry, but differing rates. The model was implemented into the OpenQuake Engine within a collaboration between GEM and SGS. Overall the results obtained with the two versions of this model show an acceptable agreement; however, there are minor differences close to the Gulf of Aqaba and in the central part of the Arabian plate.

The Earthquake Model for Central Asia (EMCA; Ullah et al., 2015) covers Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Kazakhstan, and was developed within a project lead by the GFZ German Research Centre for Geosciences. The SSC consists of a single SSM containing area sources. As in various other areas, the paucity of strong-motion recordings leads to large epistemic uncertainties that are not yet fully captured in the GMC component of the logic tree (this one created by GEM); only the active shallow crust GMC considers multiple GMMs.

Northern Asia and northeastern-most Europe use two models that together cover the entire Russian territory, split around the 76°E meridian, both developed by the GEM Hazard Team. In the Northwestern Asia model (NWA), seismicity mostly occurs within cratonic and stable crust, spanning an area of low seismic hazard. Although the coverage of this model is mostly within the European continent, many of the more productive sources in the SSM are located on the Asian continent. The model development took care to ensure full compatibility with the adjacent EMME and SHARE models. The Northeastern Asia model (NEA) covers Mongolia and the eastern part of Russia. The SSM contains a newly collected set of active faults in belts extending from southwestern Mongolia north and east to the Arctic and Pacific coasts and islands (Styron et al., 2018b), which are now part of the GAF-DB, and a model for the subduction earthquakes in the Kamchatka peninsula. The subduction sources were developed using the same methodology as for the CCA and MEX models.

The most recent national seismic hazard model for China (Gao, 2015) was implemented into the OpenQuake Engine through a collaboration with the Institute of Geophysics of the China Earthquake Administration. The SSC for this model comprises area sources that are hierarchically organized using three levels of delineation, where each level includes a further subdivision and a larger number of sources; these are used together in a single SSM, where the highest resolution delineation possible is used at each location. The GMC uses GMMs calibrated for China.

For Taiwan, we used the most recent model version produced by the Taiwan Earthquake Model (Wang et al., 2016). The SSC for this hazard model contains a single SSM consisting of area sources to model shallow distributed seismicity, and faults with simple geometry to model large earthquakes in the shallow crust, on the subduction interface, and within the subducting slab. The GMC uses GMMs calibrated for Taiwan.

For Japan, GEM collaborated with the National Research Institute for Earth Science and Disaster Resilience (NIED) to translate the 2014 version of the model developed by the HERP into the OpenQuake Engine format. The SSC for this model uniquely includes mutually exclusive ruptures on some subduction interface faults, an aspect that required new computational features in the OpenQuake Engine. The GMC uses GMMs calibrated for Japan, subdividing some of the more general tectonic contexts (e.g. subduction interface) to apply further-localized terms.

No national model for the Korean Peninsula was available, so we obtained coverage by combining elements from models of neighboring regions. The resulting SSM includes area sources from the China national model, which model shallow seismicity in stable crust, and subduction sources from the Japan national model. For the GMC, we used the recommendations of Stewart et al. (2013).

The seismic hazard model for India and the surroundings, including Nepal and Bangladesh, was developed by Nath and Thingbaijam (2012). The SSC for this model uses three SSMs: one comprising of area sources and two using smoothed seismicity but adopting different minimum magnitudes. The GMC further divides active shallow crust into two categories based on faulting mechanism. This model was implemented in the OpenQuake Engine by N. Ackerley (Natural Resources Canada).

The Southeast Asia model covers mainland Southeast Asia and Singapore. The SSC consists of two equally weighted SSMs developed independently by the Earth Observatory of Singapore and Mahidol University (Ornthammarath et al., accepted for publication). Both SSMs include fault sources; however, the geometry of key features, such as subduction interfaces, varies between the two. One SSM models distributed seismicity using area sources, while the other uses smoothed seismicity.

The Philippines is covered by a national PSHA model developed in a scientific collaboration between GEM and the Philippine Institute of Volcanology and Seismology (PHIVOLCS), which expanded upon previous work done by PHIVOLCS; a slightly updated version of the model included in the Mosaic is described in Peñarubia et al. (2020). The SSC follows the approach used for the model covering South America. The SSM includes a fault database derived from the PHIVOLCS compilation used in 2017, but with updated fault characteristics. The GMC is partially constrained by the residual analysis of Allen et al. (2014).

The Mosaic coverage of Indonesia uses the most recent national seismic hazard model, developed by a pool of local organizations in collaboration with Geoscience Australia (Irsyam et al., Submitted). Overall, the SSC structure follows the one used by the USGS for the development of the most recent hazard models for the United States and territories. Because this work built upon many years of collaboration with the USGS (e.g. Petersen et al., 2004), the model was partly implemented in OpenQuake Engine but also partly in the USGS NSHMP software, and subsequently translated into the OpenQuake Engine format.

Oceania

Oceania is covered by the national seismic hazard models for Australia, New Zealand, and Papua New Guinea, a regional model for the Pacific Islands, and the Hawaii sub-national model (Hawaii is included here given its proximity with other models covering the Pacific Ocean).

The coverage for Australia represents the latest model produced by Geoscience Australia, which was released in 2018 and is described in detail by Allen et al. (2020a, this issue). The SSC includes a logic tree with 19 independently developed SSMs based on diverse modeling assumptions, all of which have national coverage, are either peer-reviewed or submitted to conference proceedings, and are open-access. The SSMs were assigned unequal weights during compilation of the final SSC.

The New Zealand seismic hazard model is an updated version of the 2010 national seismic hazard model published by Stirling et al. (2012), the outcome of an effort involving a pool of organizations led by GNS Science. The SSC includes distributed seismicity and fault sources modeled as planar surfaces with characteristic recurrence rates. Sources follow a Poisson model of earthquake occurrence, with the exception of four fault sources with time-dependent recurrence intervals. The GMC uses GMMs calibrated for New Zealand.

For Papua New Guinea, we adopted the seismic hazard model proposed by Ghasemi et al. (2016). This model was developed within a collaboration between Geoscience Australia and the Geophysical Observatory in Port Moresby. The SSC uses two SSMs: one consisting solely of smoothed seismicity, and a second that models subduction interface seismicity with faults, and the remaining seismicity with area sources. The GMC is based partly on residual analysis performed in an earlier study by Petersen et al. (2012).

As of the Mosaic first version compilation, few recent studies had produced PSHA models for Hawaii. We chose to include the model of Klein et al. (2001). The SSC includes one SSM with fault sources modeling formerly activated volcanic flanks on Hawaii Island, and both area and gridded point sources with smoothed rates capturing the distributed seismicity. As the oldest model included in this version, the GMC includes many of the oldest GMMs used throughout the Mosaic.

Finally, the hazard model for the southern Pacific Islands was developed by the GEM Hazard Team. An updated version of the one used in the Mosaic is described by Johnson et al. (Submitted). Here, we were unable to establish a collaboration with a regional partner, and were thus dependent on global data sets and information from the literature. The model homogeneously covers the region from eastern Papua New Guinea east to American Samoa and south to New Caledonia. The SSC follows a similar methodology to that described for other models developed by GEM that encompass subduction zones, modeling subduction interfaces as faults with rates constrained by both seismicity and tectonics, and intraslab earthquakes as predefined ruptures that confine to the slab volume. Shallow crustal seismicity is modeled mostly by gridded point sources with smoothed rates but includes some faults from the global plate boundaries database of Bird (2003), which have been incorporated into the GAF-DB. The model adopts the GMC used for neighboring Papua New Guinea.

A summary of the main characteristics of models in the Mosaic

Overall, the described set of models provides a comprehensive summary of PSHA at the national and regional scales performed across the world. Here, we present a short summary of key properties, starting with a general discussion on epistemic uncertainty.

Remarkably, out of a total of 30 models, only four of them do not consider epistemic uncertainty in the GMC logic tree. GMC uncertainty is considered by defining a set of GMMs for each tectonic region considered in the logic tree. The only exception to this standard approach is the GMC logic tree used in the 2015 version of the Canada national hazard model, which captures uncertainty using a backbone approach with high, low, and mid estimates (Atkinson and Adams, 2013; Atkinson et al., 2014).

In the collection of models, the use of epistemic uncertainty in the SSC is more variable. Fifteen models incorporate this type of uncertainty (see Table 1), mainly by defining alternative SSMs that capture the variability in the geometry and location of earthquake sources and their occurrence properties. The SSC logic tree with the largest number of SSMs is the latest national hazard model for Australia (Allen et al., 2020a), which contains 19 different source models. The South Africa model (Midzi et al., 2019) is an example from this model suite that uses an alternative means of capturing source model uncertainty, as in this case the logic tree contains epistemic uncertainties on Gutenberg-Richter parameters and maximum magnitude for each individual source out of the 22 area sources considered. Other models with articulated logic tree structures (e.g. Adams et al., 2015) were implemented in the OpenQuake Engine and included in the Mosaic with their SSMs in a “collapsed” form. For SSMs with epistemic uncertainty, a collapsed SSM provides the weighted averages of the incremental occurrence rates of sources that appear in numerous logic tree branches, thus reducing the calculation complexity. Allen et al. (2020b, this issue) further explains this aspect of the implementation of Canada’s 5th Generation national seismic hazard model into the OpenQuake Engine.

We emphasize that the utility of the modeled epistemic uncertainties in a national or regional model (e.g. Gerstenberger et al., 2020) is to more robustly calculate the mean hazard. Due to the mosaic approach used here, the ranges of plausible hazard values admitted by the models cannot be compared on a global scale, since the means of accounting for epistemic uncertainty vary among models. In addition, epistemic uncertainty in the SSC for models with collapsed SSMs (CAN, USA) prohibits analysis of hazard quantiles.

With respect to the typologies of sources used in the various models, the widespread use of shallow fault sources in active and stable shallow crust is notable; 20 models use faults in crustal tectonic regimes (see Table 1). Most of the models without fault sources solely cover stable tectonic regions, where identifying active structures is in general more challenging. Overall (but excluding sources in the UCERF3 model), the Mosaic contains more than 25,000 fault sources of simple and characteristic typologies (using the OpenQuake Engine terminology) which mostly are confined to active or stable shallow crust.

In the subduction areas, common practice in the Mosaic suite of models is to separate the sources accounting for subduction interface versus intraslab seismicity. Interface sources, given their variability in geometry, are mostly modeled using complex fault geometries (Pagani et al., 2014). On the contrary, the modeling of intraslab sources is more variable. Some models (e.g. Indonesia National Hazard Model, US National Hazard Model) contain point sources obtained by smoothing seismicity within various hypocentral depth intervals, some use faults (e.g. Taiwan model), some use area

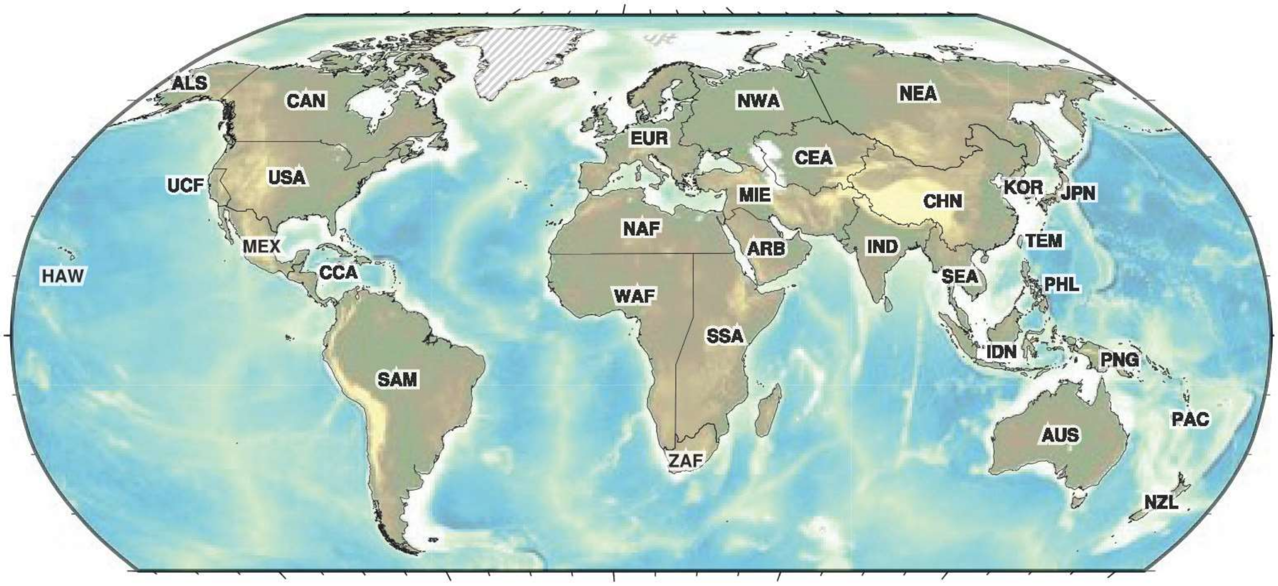


Figure 1. Geographic coverage of the models included in the Mosaic (version 2018.1). The model labeled SAM corresponds to the SARA project; CCA corresponds to the CCARA project; CEA to the EMCA project; EUR to the SHARE project; MIE to the EMME project; and SSA to the SSAHARA project, as listed in Table 1.

sources with different hypocentral depths, and some use a set of finite ruptures constrained within the slab volume.

Global hazard maps

The global hazard map released at the end of 2018 (see Figure 2) displays seismic hazard as the geographic distribution of the mean PGA with 10% probability of being exceeded (PoE) in 50 years for a reference site condition characterized by an average shear wave velocity in the range of 760 to 800 m/s in the uppermost 30 m, a range which represents rock conditions according to the large majority of classification schemes in building codes and normatives. The areas exhibiting the highest levels of seismic hazard are the coasts of the Pacific Ocean, the Himalayan thrusts, Indonesia, Turkey, and California. Overall, the Alpine-Himalayan chain is the widest band exhibiting moderate to high values of seismic hazard.

Since the Mosaic contains a variety of models created using different approaches and methodologies, the hazard results at the borders between models will in some cases inevitably show discordant values. In order to minimize these discontinuities in the pattern of hazard, and to obtain a gradual transition of the iso-probable values of shaking between models, we developed an ad hoc methodology to harmonize the hazard results across models.

Harmonization of hazard curves

The methodology adopted for combining the hazard computed with the Mosaic of models into a single, harmonized global map relies on a reference global grid of points used to calculate results; here, we use a grid geometry with near-equal-distance spacing. Every model in the Mosaic has a corresponding computation area (Figure 1) used to extract a subset of points - which we call "sites" - from this global grid. We use a buffer distance (b) of about 90 km around each computation area in order to have a sufficiently large band of overlapping sites across each border between adjacent models.

We obtain a global harmonized hazard map of mean PGA on rock (here, just called "hazard") using a two-phase process. First, we sequentially compute the hazard for each model. For sites inside the zone of model coverage, and not within the buffer distance of the model perimeter, we store the

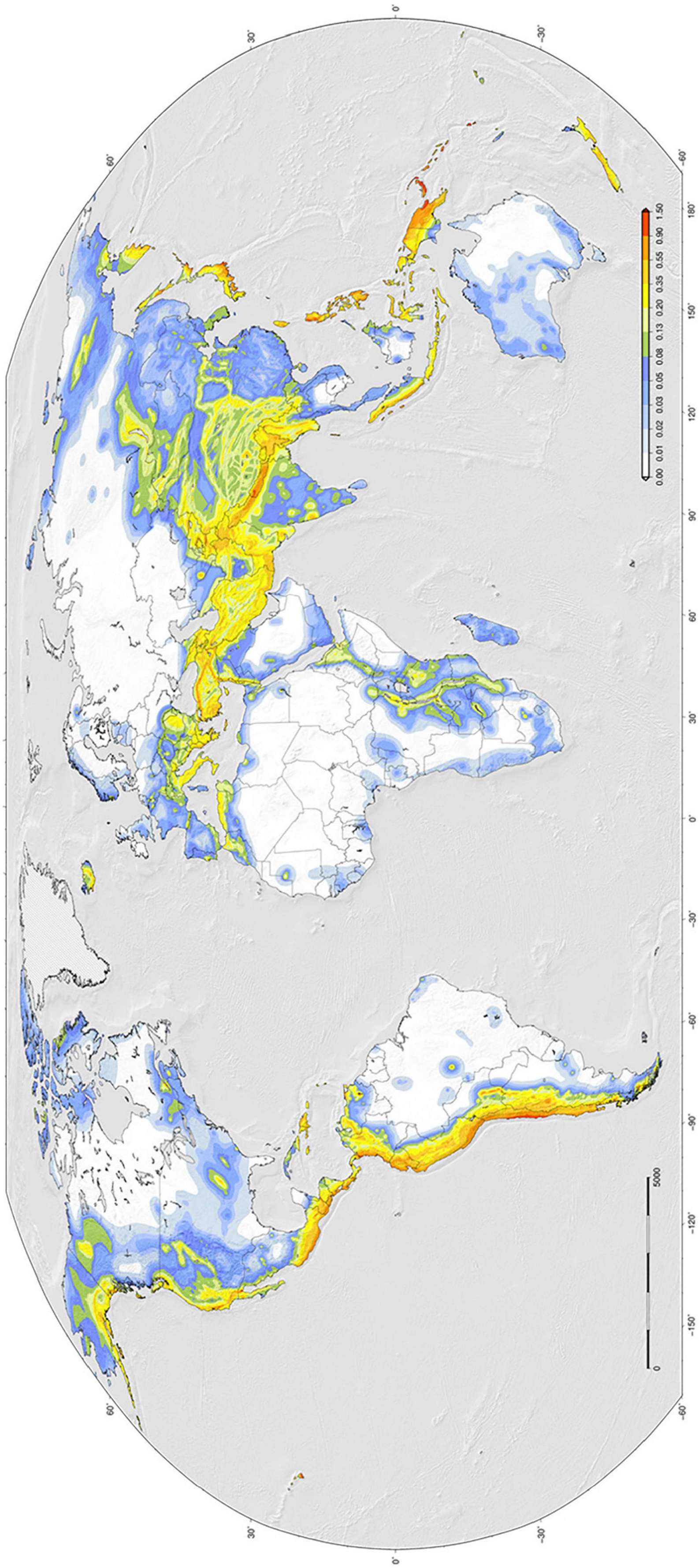
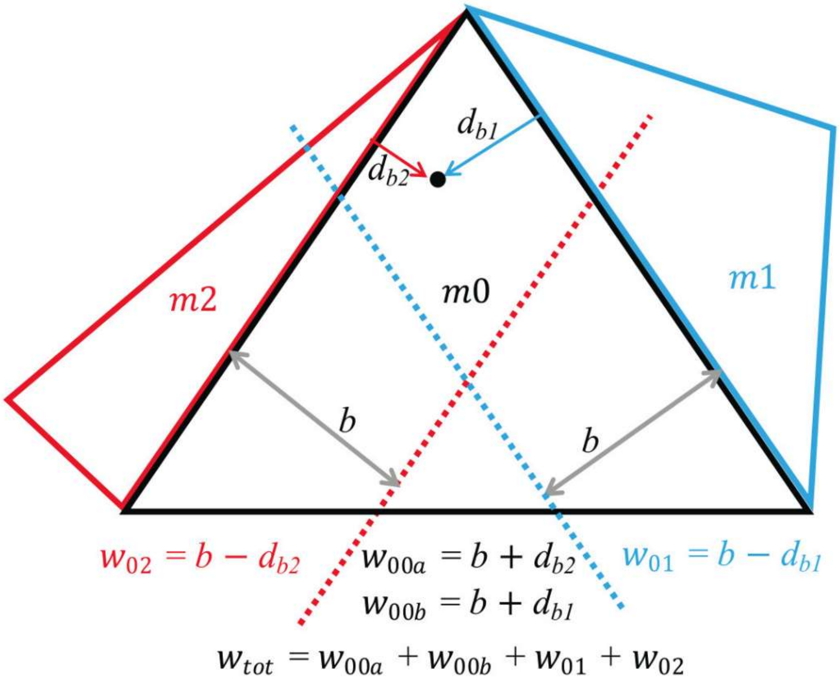


Figure 2. *The GEM global hazard map (version 2018.1). The map displays mean peak ground acceleration (PGA in units of g) with a 10% probability of being in exceeded in 50 years on reference soil conditions (V_{s30} = 760–800 m/s).*



$$\boxed{afe_{iml} = afe^{0}_{iml} * \frac{w_{00a}}{w_{tot}} + afe^{0}_{iml} * \frac{w_{00b}}{w_{tot}} + afe^{1}_{iml} * \frac{w_{01}}{w_{tot}} + afe^{2}_{iml} * \frac{w_{02}}{w_{tot}}}$$

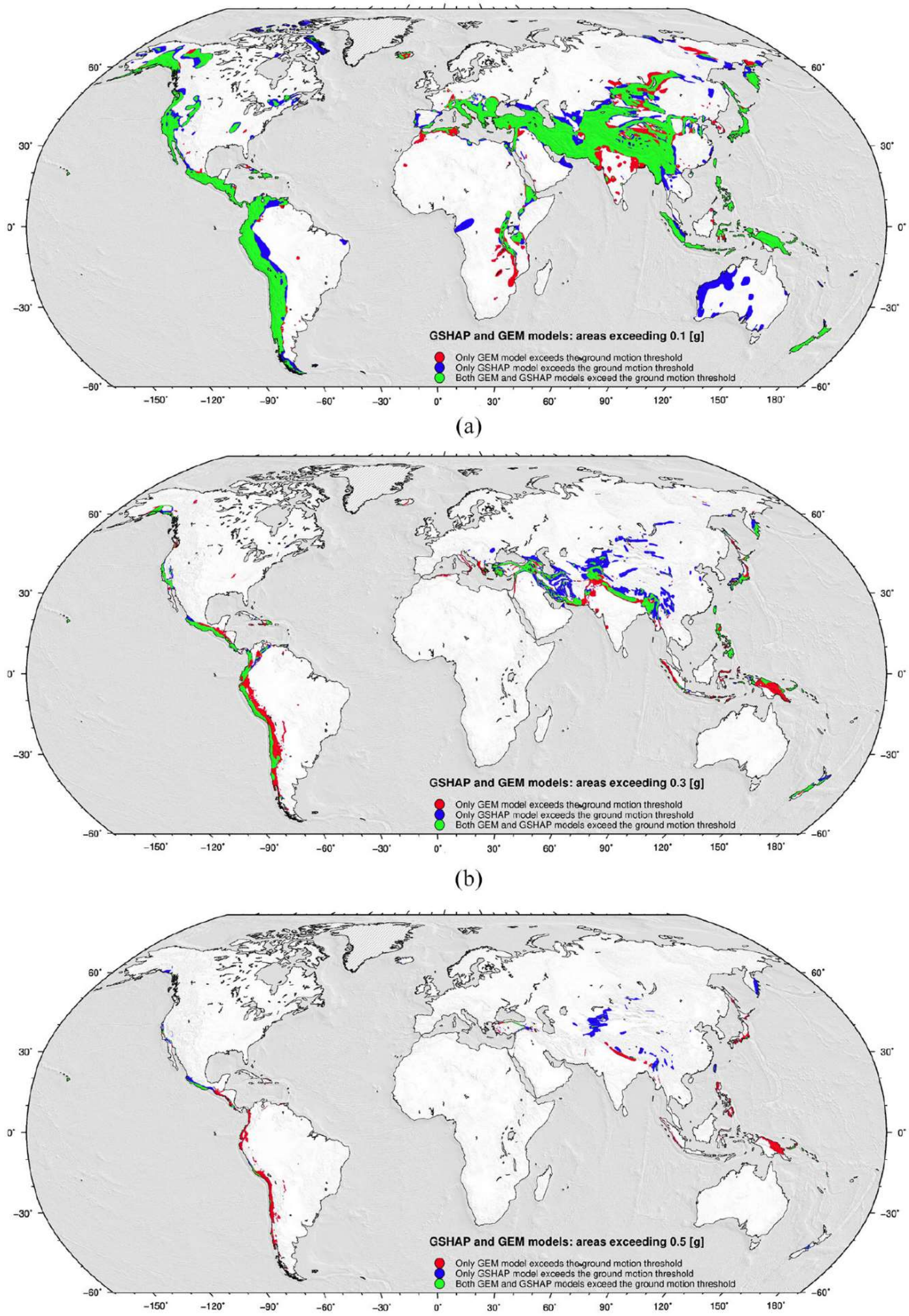
Figure 3. *This schematic shows how the harmonized hazard curve is resolved for a site that occurs within the buffer of one or more models. In this case, the site (black dot) occurs within the buffer zone of models m1 and m2, and inside of model m0. The hazard curve from model m0 is assigned the most weight. The hazard curve from model m2 is assigned a higher weight than that from model m1, since the site is closer to m2 (e.g.* $d_{b2} \backslash d_{b1}$*). The initial weights are normalized by the sum of all four weights, and then the normalized weights are used to sum the annual frequency of exceedance (afe) for any given intensity measure level (iml) for all the curves in question according to the boxed equation.*

---

hazard curve for each site in a final repository; if the site is within the buffer distance of a region's perimeter, we store the hazard curve in a separate, temporary repository. In a second phase, we further process the hazard curves for onshore sites that have multiple stored hazard curves, for example, in the buffer regions. In most cases, sites within an onshore buffer region have two hazard curves, one for each model across which the buffer is placed. A minor number of sites concentrated in Asia are assigned more than two hazard curves, for example, near the contact between the models of China, Central Asia, the Middle East, and India.

The final, harmonized hazard curve for each site is computed from the collocated hazard curves in the temporary repository. For each site, we compute the shortest distance to the border between models, d_b, and use this distance to compute a weight for each hazard curve (see Figure 3). Hazard curves inside the zone of model coverage have a larger contribution to the final hazard curve and are assigned an initial weight $w_0 = b + d_b$; on the contrary, hazard curves that are outside the perimeter of their model's coverage are assigned an initial weight $w_0 = b - d_b$. Weights are subsequently normalized by the sum of all weights for collocated hazard curves, yielding the fractional contribution of each. Finally, the collocated hazard curves, scaled by their respective coefficients (w^{in} or w^{out_i}), are summed to yield the final, harmonized hazard curves. For a given site, each ordinate of the hazard curve is obtained as follows:

$$afe_{iml} = \sum_{i=1}^{n} afe^{in}_{iml} \times w^{in} + afe^{out_i}_{iml} \times w^{out_i} \qquad (1)$$



(a)

(b)

(c)

Figure 4. *Maps comparing the pattern of hazard included in the GSHAP and GEM (version 2018.1) global hazard maps. Given a reference ground motion threshold* ($\mathrm{gm_T}$)*, the green-filled areas show where both the GSHAP map and the GEM map contain values of ground motion larger than* $\mathrm{gm_T}$*, the blue-filled areas show the domains where only the GSHAP model exceeds* $\mathrm{gm_T}$*, and the red-filled areas show the regions where only the GEM map has values of hazard higher than the threshold ground motion* $\mathrm{gm_T}$*: (a)* $\mathrm{gm_T} = 0.1g$*, (b)* $\mathrm{gm_T} = 0.3g$*, and (c)* $\mathrm{gm_T} = 0.5g$*.*

where i iterates through the number n of model borders involved.

Notably, from a purely scientific perspective, the hazard map obtained through this harmonization procedure might obscure potential hazard differences at the borders between models. Scientists interested in studying those differences are invited to use results directly obtained for individual models using the OpenQuake Engine.

Comparisons with previous data and models

Over the last 20 years, the hazard map produced by the GSHAP project (Giardini et al., 1999) represented a benchmark for depicting probabilistic seismic hazard at a global scale. In this section, we illustrate similarities and fundamental differences between the GSHAP map and the GEM map presented herein. Both the maps display mean PGA on rock with 10% Probability of Exceedance (PoE) in 50 years.

We discuss our assessment using the maps in Figure 4. Each map contains areas filled with three colors which indicate the following: given a reference ground motion threshold (gm_T) (e.g. $0.1g$), the green-filled areas show where both the GSHAP map and the GEM map contain values of ground motion larger than gm_T, the blue-filled areas show the domains where only the GSHAP model exceeds gm_T, and the red-filled areas show the regions where only the GEM map has values of hazard higher than the threshold ground motion gm_T.

Figure 4a shows the map obtained for a gm_T equal to $0.1g$. Overall, the two maps exhibit compatible results but with noticeable differences in a few key regions. Some of the most striking differences appear in Australia, Northeastern Canada, and the Caucasus, where the GSHAP map shows higher values of hazard, and India and the southern part of the East African Rift, where the hazard included in the GEM model shows higher values.

In Figure 4b, the gm_T is increased to $0.3g$, and the differences between hazard pattern in the two maps become more evident. In Asia, with the exception of India and south Pakistan, the GSHAP model shows more regions where the hazard exceeds the gm_T compared to the GEM map. The GEM map, on the contrary, indicates more prominent hazard than GSHAP in South America along the Andean Cordillera, in Central America, in Papua New Guinea, Indonesia, and southeastern coastal Japan. On a coarser scale, we note that the GEM map tends to concentrate high hazard areas along major subduction regions, whereas the GSHAP map shows more hazard along the Alpine-Himalayan orogenic belt.

The same trend is substantiated by the map in Figure 4c, computed for a gm_T of $0.5g$. In this plot the congruity of the two maps reduces even further and, as a consequence, the green-filled areas almost completely disappear. Red-filled areas with higher GEM values confine to the proximity of subduction regions, including the Himalayan thrusts, with the exception of Mexico, where the two maps both exceed the gm_T of $0.5g$. The blue-filled zones with higher GSHAP values are mostly concentrated in Asia (China, Hindu Kush, and Kamchatka).

Conclusion

The GEM global hazard map and the Mosaic - the underlying database of hazard input models - are the result of a major collective effort, which saw the contribution of dozens of organizations and individuals. Because of this, the Mosaic is a comprehensive summary of recent, publicly accessible hazard input models developed at national and regional scale produced globally over the last ten years. A second important outcome of this effort is the framework for the Mosaic, which - among other contributions - facilitates the preparation of global-scale seismic hazard maps.

The GEM global hazard map released at the end of 2018 constitutes an update of hazard computed at the global scale using a collection of hazard models, as originally done within the GSHAP project (Giardini et al., 1999). The GSHAP and GEM hazard maps show similar patterns of hazard when we consider the exceedance of moderate levels of hazard for a reference return period of 475 years (corresponding to 10% PoE in 50 years), while the two maps exhibit more dissimilarity in geographic distributions considering the areas affected by the highest levels of hazard. The GEM map identifies the areas located in the proximity of the most important subduction sources as the most dangerous ones, whereas the GSHAP map highlighted sections of the Alpine-Himalayan orogenic belt.

We hope that the Mosaic will promote a collaborative, bottom-up approach to the construction of more homogeneous seismic hazard models, notwithstanding the difficulty of properly defining what exactly represents a set of homogeneous hazard models. In our opinion, the degree of homogeneity between the SSC in two different hazard input models must be analyzed by considering the adopted methodologies, the information used, and the tectonic context covered. The latter is important since the methods used to build models often depend on the tectonic region in question. Differences between SSCs can also be assessed during a posteriori tests of the models, for example, through comparisons between the predicted earthquake occurrences and the observations collected after the release of the model. The homogeneity between distinct GMCs is easier to compare, as it depends on the GMMs selected per tectonic region and their similarity. In the coming years, GEM plans to explore ways to compare hazard models with the aim to promote discussion and development of more homogeneous and conceptually compatible seismic hazard models. This will start with the creation of a more comprehensive set of tools for comparing various characteristics between models (see, for example, Pagani et al., 2016) and between hazard models and basic information used for their construction, such as earthquake catalogs, fault databases, tectonic and geodetic information, and strong-motion data.

As a database, the Mosaic offers a number of scientific opportunities, and supplies hazard information for some parts of the globe that was previously unavailable. Its accessibility to the scientific community gives it the potential to serve as a modern benchmark for newly developed models, which might later be incorporated into the collection. Notably, components of the Mosaic fill knowledge gaps in regions that were previously only partially covered by updated models, such as in some parts of Africa. More generally, the Mosaic has the potential to promote innovations and a more thorough understanding of our current state of knowledge, starting from the most important and challenging issues that will be faced when new models are constructed in the various tectonic regions. The first version of the Mosaic includes a number of novelties in terms of modeling practices, including mutually exclusive ruptures (JPN), unconventional rupture configurations (UCERF), approaches to pooling expert knowledge (AUS), and adjusted backbone GMMs (CAN), which can serve as examples to modelers investigating other regions. In addition to risk calculations, research in related fields could be developed on top of the Mosaic models, such as the study of secondary hazards, the incorporation of aftershock contribution into regular hazard analyses, and infrastructure risk.

Alongside the benefits and potential opportunities of the Mosaic are some limitations inherent to the mosaic approach. Here, we have restricted our presentation of the Mosaic to the mean PGA on rock; the discussion of other intensity metrics and site conditions is less straightforward. The GMCs of the models are constrained by the flexibility inherited from their GMMs. For example, the GMMs included in each GMC are not systematically calibrated for all spectral periods; in the most extreme case, the GMC for Japan (HERP, 2014) only applies to peak ground motions (acceleration and velocity) and does not include coefficients for higher spectral periods. In addition, some of the GMMs selected by the model authors do not include a site condition term, and thus can only be applied for a tight range of Vs30 values. These latter restrictions required us to define more comprehensive or flexible GMCs for use in certain applications, such as in the global risk calculations described by Silva et al. (2020).

The Mosaic is built upon a dynamic framework, that includes the OpenQuake Engine, the open-source tools developed by GEM and partner organizations for the construction of hazard input model components, and the collection of hazard models described in this article. This framework will be maintained as part of the GEM Hazard Team activities to include up-to-date openly available hazard information, and has undergone a number of developments in the months since its initial release. At the time of publication, the Mosaic now incorporates new or updated models developed collaboratively by GEM and scientific institutions, for example, for the Philippines (Peñarubia et al., 2020), improvements to existing models, such as the addition of the cluster model to USA, and the application of new methodologies for modeling hazard in subduction zones (Pagani et al., 2020). The global hazard map has been updated to reflect these changes. Additional maps have also been produced depicting global seismic hazard for various spectral ordinates, return periods, and considering non-uniform soil conditions by approximating V_{s30} using topographic slope (Allen and Wald, 2009; Wald and Allen, 2007). GEM aims to continue to incorporate updates of existing models and to expand the number of Tier 1 hazard models included in the Mosaic. Both these efforts will be carried out, to the extent possible, with the largest participation of experts from various regions of the world. The map will be updated using current versions of the GEM Mosaic on an approximately yearly basis.

The various components of the Mosaic not yet accessible are expected to be released throughout 2020 and 2021, thus allowing researchers and practitioners to independently validate data and models and to reproduce the seismic risk estimates, and hopefully assist in further advancement of GEM models through community efforts.

Acknowledgments

This contribution would not have been possible without the support and enthusiasm of GEM's public and private sponsors during the Foundation's second implementation phase (2014–2018). We thank the many organizations and individuals involved in this effort via projects, collaborations, and otherwise, and those that continue to show support for the future of the GEM hazard mosaic. We also thank all the GEM Secretariat staff, including former members, for their support. The comments and suggestions provided by three anonymous reviewers and the Associated Editor T. Allen help to considerably improve the quality of this paper. Maps were plotted using the Generic Mapping Tools software (Wessel et al., 2013).

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Marco Pagani https://orcid.org/0000-0001-8125-1925
Robin Gee https://orcid.org/0000-0002-7920-6444
Kendra Johnson https://orcid.org/0000-0003-1369-5158
Valerio Poggi https://orcid.org/0000-0001-8336-3445
Richard Styron https://orcid.org/0000-0002-2374-9431
Graeme Weatherill https://orcid.org/0000-0001-9347-2282

References

Adams J, Halchuk S, Allen T and Rogers G (2015) Canada's 5th generation seismic hazard model, as prepared for the 2015 National Building Code of Canada. In: Proceedings of the 11th Canadian conference on earthquake engineering, 21–24 July.

Ahulu ST, Danuor SK and Asiedu DK (2018) Probabilistic seismic hazard assessment of southern part of Ghana. Journal of Seismology 22: 539–557.

Albini P, Musson RMW, Rovida A, Locati M, Gomez Capera AA and Viganò D (2014) The global earthquake history.

Earthquake Spectra 30: 607‐624.

Allen T, Ryu H, Bautista B, Bautista ML, Narag I, Sevilla WI, Melosantos MLP, Papiona K and Bonita J (2014) Enhancing risk analysis capacities for flood, tropical cyclone severe wind and earthquake for the greater metro manila area, component 5. Technical report, Philippine Institute of Volcanology and Seismology Geoscience Australia, Philippine.

Allen TI and Wald DJ (2009) On the use of high-resolution topographic data as a proxy for seismic site conditions (VS 30). Bulletin of the Seismological Society of America 99: 935‐943.

Allen TI, Griffin JD, Leonard M, Clark DJ and Ghasemi H (2020a) The 2018 national seismic hazard assessment of Australia: Quantifying hazard changes and model uncertainties. Earthquake Spectra 36(S1): 5‐43.

Allen TI, Halchuk S, Adams J and Weatherill GA (2020b) Forensic PSHA: Benchmarking Canada's Fifth Generation seismic hazard model using the OpenQuake-engine. Earthquake Spectra 36(S1): 91‐111.

Amponsah P, Leydecker G and Muff R (2012) Earthquake catalogue of Ghana for the time period 1615‐2003 with special reference to the tectono-structural evolution of south-east Ghana. Journal of African Earth Sciences 75: 1‐13.

Amponsah PE (2004) Seismic activity in Ghana: Past, present and future. Annals of Geophysics 47: 539‐543.

Atkinson GM and Adams J (2013) Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps. Canadian Journal of Civil Engineering 40: 988‐998.

Atkinson GM, Bommer JJ and Abrahamson NA (2014) Alternative approaches to modeling epistemic uncertainty in ground motions in probabilistic seismic-hazard analysis. Seismological Research Letters 85: 1141‐1144.

Balassanian S, Ashirov T, Chelidze T, Gassanov A, Kondorskaya N, Molchan G, Pustovitenko B, Trifonov V, Ulomov V and Giardini D (1999) Seismic hazard assessment for the Caucasus test area. Annals of Geophysics 42: 1139‐1151.

Basham P and Giardini D (1993) Technical guidelines for global seismic hazard assessment. Annals of Geophysics 36: 15‐24.

Bird P (2003) An updated digital model of plate boundaries. Geochemistry, Geophysics, Geosystems 4: 1027.

Chen Y-S, Weatherill G, Pagani M and Cotton F (2018) A transparent and data-driven global tectonic regionalization model for seismic hazard assessment. Geophysical Journal International 213: 1263‐1280.

Christophersen A, Litchfield N, Berryman K, Thomas R, Basili R, Wallace L, Ries W, Hayes GP, Haller KM, Yoshioka T, Koehler RD, Clark D, Wolfson-Schwehr M, Boettcher MS, Villamor P, Horspool N, Ornthammarath T, Zuñiga R, Langridge RM, Stirling MW, Goded T, Costa C and Yeats R (2015) Development of the Global Earthquake Model's neotectonic fault database. Natural Hazards 79: 111‐135.

Danciu L, Kale Ö and Akkar S (2018a) The 2014 earthquake model of the Middle East: Ground motion model and uncertainties. Bulletin of Earthquake Engineering 16: 3497‐3533. Available at: https://doi.org/10.1007/s10518-016-9989-1

Danciu L, Şeşetyan K, Demircioglu M, Gülen L, Zare M, Basili R, Elias A, Adamia S, Tsereteli N, Yalcxın H, Utkucu M, Khan MA, Sayab M, Hessami K, Rovida AN, Stucchi M, Burg J-P, Karakhanian A, Babayan H, Avanesyan M, Mammadli T, Al-Qaryouti M, Kalafat D, Varazanashvili O, Erdik M and Giardini D (2018b) The 2014 earthquake model of the Middle East: Seismogenic sources. Bulletin of Earthquake Engineering 16: 3465‐3496. Available at: https://doi.org/10.1007/s10518-017-0096-8

Dimaté C, Drake L, Yepez H, Ocola L, Rendon H, Grünthal G and Giardini D (1999) Seismic hazard assessment in the Northern Andes (PILOTO Project). Annals of Geophysics 42: 1039‐1055.

Drouet S, Montalva G, Dimaté MC, Castillo LF and Fernandez GA (2017) Building a Ground-Motion Logic Tree for South America within the GEM-SARA project framework. In: Proceedings of the 16th world conference on earthquake engineering, Santiago, 9‐13 January.

Field EH, Arrowsmith RJ, Biasi GP, Bird P, Dawson TE, Felzer KR, Jackson DD, Johnson KM, Jordan TH, Madden C, Michael AJ, Milner KR, Page MT, Parsons T, Powers PM, Shaw BE, Thatcher WR, Weldon RJ and Zeng Y (2014) Uniform California Earthquake rupture forecast, version 3 (UCERF3)—The time-independent model. Bulletin of the Seismological Society of America 104: 1122‐1180.

Gao M (2015) Publicizing Textbook of China Seismic Hazard Map. Beijing: China Standard Press (in Chinese).

Garcia J, Weatherill GW, Pagani M, Rodriguez L and Poggi V and the SARA Working Group (2017) Building an open seismic hazard model for South America: The SARA-PSHA model. In: Proceedings of the 16th world conference on earthquake engineering, Santiago, 9‐13 January.

Gerstenberger MC, Marzocchi W, Allen T, Pagani M, Adams J, Danciu L, Field EH, Fujiwara H, Luco N, Ma K‐F, Meletti C and Petersen MD (2020) Probabilistic seismic hazard analysis at regional and national scales: State of the art and future challenges. Reviews of Geophysics 58: e2019RG000653. Available at: https://doi.org/10.1029/2019RG000653

Ghasemi H, McKee C, Leonard M, Cummins P, Moihoi M, Spiro S, Taranu F and Buri E (2016) Probabilistic seismic hazard map of Papua New Guinea. Natural Hazards 81: 1003‐1025.

Giardini D, Grünthal G, Shedlock KM and Zhang P (1999) The GSHAP global seismic hazard map. Annali di Geofisica 42: 1225‐1230.

Giardini D, Woessner J and Danciu L (2014) Mapping Europe's seismic hazard. EOS 95: 261‐262.

Headquarters for Earthquake Research Promotion (HERP) (2014) The National Seismic Hazard Map 2014 version—with an overview on the ground motion hazard of the whole country. Technical report, Headquarters for Earthquake

Research Promotion (in Japanese). Available at: https://www.jishin.go.jp/evaluation/seismic_hazard_map/shm_report/shm_report_2014/ (last accessed June 2020).

Hiemer S, Woessner J, Basili R, Danciu L, Giardini D and Wiemer S (2014) A smoothed stochastic earthquake rate model considering seismicity and fault moment release for Europe. Geophysical Journal International 198: 1159‐1172.

Irsyam M, Cummins P, Asrurifak M, Faisal L, Natawidjaja DH, Widiyantoro S, Meilano I, Triyoso W, Rudiyanto A, Hidayati S, Ridwan M, Hanifa NR and Syahbana AJ (2020) Development of the 2017 national seismic hazard maps of Indonesia. Earthquake Spectra 36(S1): 112‐136.

Johnson KL, Pagani M and Styron R (Submitted) Seismic Hazard model for the pacific Islands. Geophysical Journal International.

Klein FW, Frankel AD, Mueller CS, Wesson RL and Okubo PG (2001) Seismic Hazard in Hawaii: High rate of large earthquakes and probabilistic ground-motion maps. Bulletin of the Seismological Society of America 91: 479‐498.

Kreemer C, Blewitt G and Klein EC (2014) A geodetic plate motion and Global Strain Rate Model. Geochemistry, Geophysics, Geosystems 15: 3849‐3889.

Midzi V, Manzunzu B, Mulabisana T, Zulu BS, Pule T and Myendeki S (2020) Probabilistic seismic hazard maps for South Africa. Journal of African Earth Sciences 162: 103689.

Midzi V, Manzunzu B, Mulabisana T, Zulu BS, Pule T, Myendeki S and Rathod GW (2019) The probabilistic seismic hazard assessment of South Africa. Journal of African Earth Sciences, 162. DOI: https://doi.org/10.1016/j.jafrearsci.2019.103689.

Nath SK and Thingbaijam KKS (2012) Probabilistic seismic hazard assessment of India. Seismological Research Letters 83: 135‐149.

Ordaz MG, Cardona O-D, Salgado-Gálvez MA, Bernal-Granados GA, Singh SK and Zuloaga-Romero D (2014) Probabilistic seismic hazard assessment at global level. International Journal of Disaster Risk Reduction 10: 419‐427.

Ornthammarath T, Warnitchai P, Chan C-H, Wang Y, Shi X, Nguyen PH, Nguyen JM, Kosuwan S and Thant M (2020) Probabilistic Seismic hazard assessments for Northern Southeast Asia (Indochina): Smooth seismicity approach. Earthquake Spectra 36(S1): 69‐90.

Pagani M, Garcia J, Monelli D, Weatherill G and Smolka A (2015) A summary of hazard datasets and guidelines supported by the Global Earthquake Model during the first implementation phase. Annals of Geophysics 58: S0108.

Pagani M, Garcia-Pelaez J, Gee R, Johnson K, Poggi V, Styron R, Weatherill G, Simionato M, Viganò D, Danciu L and Monelli D (2018) Global Earthquake Model (GEM) Seismic Hazard Map (version 2018.1–December 2018). DOI: 10.13117/GEM-GLOBAL-SEISMIC-HAZARDMAP-2018

Pagani M, Hao KX, Fujiwara H, Gerstenberger M and Ma K-F (2016) Appraising the PSHA Earthquake Source Models of Japan, New Zealand, and Taiwan. Seismological Research Letters 87: 1240‐1253.

Pagani M, Johnson K and Garcia Palaez J (2020) Modelling subduction sources for probabilistic seismic hazard analysis. Geological Society, London, Special Publications, 501, https://doi.org/10.1144/ SP501-2019-120

Pagani M, Monelli D, Weatherill G, Danciu L, Crowley H, Silva V, Henshaw P, Butler L, Nastasi M, Panzeri L, Simionato M and Viganò D (2014) OpenQuake engine: An open hazard (and risk) software for the Global Earthquake Model. Seismological Research Letters 85: 692‐702.

Peñarubia HC, Johnson KL, Styron RH, Bacolcol TC, Sevilla WIG, Perez JS, Bonita JD, Narag IC, Solidum RU, Pagani MM and Allen TI (2020) Probabilistic seismic hazard analysis model for the Philippines. Earthquake Spectra 36(S1): 44‐68.

Petersen MD, Dewey J, Hartzell S, Mueller C, Harmsen S, Frankel A and Rukstales K (2004) Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula. Tectonophysics 390: 141‐158.

Petersen MD, Harmsen SC, Jaiswal KS, Rukstales KS, Luco N, Haller KM, Mueller CS and Shumway AM (2018) Seismic hazard, risk, and design for South America. Bulletin of the Seismological Society of America 108: 781‐800.

Petersen MD, Harmsen SC, Rukstales KS, Mueller CS, McNamara DE, Luco N and Walling M (2012) Seismic Hazard of American Samoa and Neighboring South Pacific Islands–Methods, Data, Parameters, and Results. Open-File Report 2012‐1087, 7 August. Denver, CO: US Department of the Interior, US Geological Survey.

Petersen MD, Moschetti MP, Powers PM, Mueller CS, Haller KM, Frankel AD, Zeng Y, Rezaeian S, Harmsen SC, Boyd OS, Field E, Chen R, Rukstales KS, Luco N, Wheeler RL, Williams RA and Olsen AA (2014) Documentation for the 2014 update of the United States national seismic hazard maps. Open-file report 2014‐1091, 17 July. Denver, CO: US Geological Survey.

Petersen MD, Moschetti MP, Powers PM, Mueller CS, Haller KM, Frankel AD, Zeng Y, Rezaeian S, Harmsen SC, Boyd OS, Field N, Chen R, Rukstales KS, Luco N, Wheeler RL, Williams RA and Olsen AH (2015) The 2014 United States national seismic hazard model. Earthquake Spectra 31: S1‐S30.

Poggi V, Durrheim R, Tuluka GM, Weatherill G, Gee R, Pagani M, Nyblade A and Delvaux D (2017) Assessing seismic hazard of the East African Rift: A pilot study from GEM and AfricaArray. Bulletin of Earthquake Engineering 15: 4499‐4529.

Poggi V, Garcia-Pelàez J, Styron R, Pagani M and Gee R (2020) A probabilistic seismic hazard model for North Africa. Bulletin of Earthquake Engineering 18: 2917‐2951.

Şeşetyan K, Danciu L, Demircioğlu Tümsa MB, Giardini D, Erdik M, Akkar Gülen SL, Zare M, Adamia S, Ansari A, Arakelyan A, Askan A, Avanesyan M, Babayan H, Chelidze T, Durgaryan R, Elias A, Hamzehloo H, Hessami K, Kalafat D, Kale O, Karakhanyan A, Khan MA, Mammadli T, Al-Qaryouti M, Sayab M, Tsereteli N, Utkucu M, Varazanashvili O, Waseem M, Yalcxın H and Yımaz MT (2018) The 2014 seismic hazard model of the Middle East: Overview and results. Bulletin of Earthquake Engineering 16: 3535‑3566.

Silva V, Amo-Oduro D, Calderon A, Costa C, Dabbeek J, Despotaki V, Martins L, Pagani M, Rao A, Simionato M, Viganò D, Yepes-Estrada C, Acevedo A, Crowley H, Horspool N, Jaiswal K, Journeay M and Pittore M (2019) Development of a global seismic risk model. Earthquake Spectra 36(S1): 372‑394.

Stewart JP, Douglas J, Javanbarg M, Bozorgnia Y, Abrahamson NA, Boore DM, Campbell KW, Delavaud E, ErdikM and Stafford PJ (2013) Selection of ground motion prediction equations for the Global Earthquake Model. Earthquake Spectra 31: 19‑45.

Stirling M, McVerry G, Gerstenberger M, Litchfield N, Dissen RV, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, Lamarche G, Nodder S, Reyners M, Bradley B, Rhoades D, Smith W, Nicol A, Pettinga J, Clark K and Jacobs K (2012) National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America 102: 1514‑1542.

Storchak DA, Giacomo DD, Bondàr I, Engdahl ER, Harris J, Lee WHK, Villaseñor A and Bormann P (2013) Public release of the ISC‑GEM global instrumental earthquake catalogue (1900‑2009). Seismological Research Letters 84: 810‑815.

Styron R and Pagani M (2020) The GEM global active faults database. Earthquake Spectra 36(S1): 160‑180.

Styron R and Poggi V (2018) GEM North Africa active fault database. DOI: 10.13117/N-AFRICAACTIVE-FAULTS.

Styron R, García-Pelaez J and Pagani M (2018a) GEM Central America and Caribbean active faults database. DOI: 10.5281/zenodo.3376300.

Styron R, Garcia-Pelaez J and Pagani M (2020) CCAF-DB: The Caribbean and Central American active fault database. Natural Hazards and Earth System Science 20: 831‑857. Available at: https://doi.org/10.5194/nhess-20-831-2020

Styron R, Poggi V and Lunina OV (2018b) GEM Northeastern Asia active fault database.

Ullah S, Bindi D, Pilz M, Danciu L, Weatherill G, Zuccolo E, Ischuk A, Mikhailova NN, Abdrakhmatov K and Parolai S (2015) Probabilistic seismic hazard assessment for Central Asia. Annals of Geophysics 58: S0103.

Villegas GC, Mendoza C and Ferrari L (2017) Mexico quaternary fault database. Terra Digitalis 1: 1‑9.

Wald DJ and Allen TI (2007) Topographic slope as a proxy for seismic site conditions and amplification. Bulletin of the Seismological Society of America 97: 1379‑1395.

Wang Y-J, Chan C-H, Lee Y-T, Ma K-F, Shyu JBH, Rau R-J and Cheng C-T (2016) Probabilistic seismic hazard assessments for Taiwan. Terrestrial Atmospheric and Oceanic Sciences 27: 325‑340.

Weatherill GA and Pagani M (2014) From smoothed seismicity forecasts to probabilistic seismic hazard: Insights and challenges from a global perspective. In: Proceedings of the second European conference on earthquake engineering and seismology, Istanbul, 25‑29 August.

Weatherill GA, Pagani M and Garcia J (2016) Exploring earthquake databases for the creation of magnitude-homogeneous catalogues: Tools for application on a regional and global scale. Geophysical Journal International 206: 1652‑1676.

Wessel P, Smith WFH, Scharroo R, Luis J and Wobbe F (2013) Generic mapping tools: Improved version released. Eos, Transactions, American Geophysical Union 94: 209‑210.

Wesson RL, Boyd OS, Mueller CS and Frankel AD (2008) Challenges in making a seismic hazard map for Alaska and the Aleutians. Active Tectonics and Seismic Potential of Alaska Geophysical Monograph Series 179: 385‑397.

Wesson RL, Boyd OS, Mueller CS, Bufe CG, Frankel AD and Petersen MD (2007) Revision of time-independent probabilistic seismic hazard maps for Alaska. Open-File Report 2007‑1043, U.S. Geological Survey, Reston, Virginia.

Woessner J, Danciu L, Giardini D, Crowley H, Cotton F, Grünthal G, Valensise G, Arvidsson R, Basili R, Demircioglu MB, Hiemer S, Meletti C, Musson RW, Rovida AN, Sesetyan K and Stucchi M and The SHARE Consortium (2015) The 2013 European seismic hazard model: Key components and results. Bulletin of Earthquake Engineering 13: 3553‑3596.

Zahran HM, Sokolov V, Roobol MJ, Stewart IC, Youssef SE-H and El-Hadidy M (2016) On the development of a seismic source zonation model for seismic hazard assessment in western Saudi Arabia. Journal of Seismology 20: 747‑769.

Zahran HM, Sokolov V, Youssef SE-H and Alraddadi WW (2015) Preliminary probabilistic seismic hazard assessment for the Kingdom of Saudi Arabia based on combined areal source model: Monte Carlo approach and sensitivity analyses. Soil Dynamics and Earthquake Engineering 77: 453‑468.

Zare M, Amini H, Yazdi P, Sesetyan K, Demircioglu MB, Kalafat D, Erdik M, Giardini D, Khan MA and Tsereteli N (2014) Recent developments of the Middle East catalog. Journal of Seismology 18: 749‑772.