The 2018 version of the Global Earthquake Model: Hazard component

M. Pagani,[a] J. Garcia-Pelaez,[a] R. Gee,[a] K. Johnson,[a] V. Silva,[b] M. Simionato,[c] R. Styron,[a] D. Viganò,[c] L. Danciu,[d] D. Monelli,[e] V. Poggi,[f] and G. Weatherill[g]

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. Overall, the map and the underlying database of models provide the most 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 can be created. 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 a given area, priority was given to seismic hazard models either developed by well-recognized national agencies or by large collaborative projects involving local scientists. The presented version of the GEM mosaic contains 30 probabilistic seismic hazard models, 14 of which represent national or sub-national models. The remainder are regional-scale models built by GEM itself using open tools and methodologies.

INTRODUCTION

Seismic hazard maps depict the geographic distribution of shaking intensity with a given annual frequency (or probability) of exceedance. An alternative, although less common way to portray the geographic distribution seismic hazard is the annual frequency (or probability) of exceedance of a fixed ground motion level of an intensity measure type (e.g. peak ground

[a] Hazard Team, Global Earthquake Model, Pavia, Italy
[b] Risk Team, Global Earthquake Model, Pavia, Italy
[c] IT Team, Global Earthquake Model, Pavia, Italy
[d] Swiss Seismological Service, ETH, Zurich, Switzerland
[e] Tokyo Millennium, Zurich, Switzerland
[f] Centro Ricerche Sismologiche, OGS, Trieste, Italy
[g] GFZ German Research Centre for Geosciences, Potsdam, Germany

acceleration).

Hazard analyses are commonly classified based on the extent of the area covered by the analysis. Typical scales of investigation include site-specific studies, seismic microzonations, 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 “rock” (or reference site conditions). Global seismic hazard maps, such as the map presented here, inform specialists and common people about the most seismically dangerous regions of the world.

Two approaches are available for constructing a global seismic hazard model and the subsequent calculation of hazard. The first one involves subdividing inland territories into a number of areas and constructing independent hazard models for each of them. 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. The second approach tackles the problem more radically by building a single seismic hazard model using fewer, but more homogenous, methods and a 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 are probably different, and the basic data sets are likely compiled following different criteria and may exhibit different levels of completeness. 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. Not only does the latter approach diminish the role and contributions of the earthquake hazard community, however, it may not even fully guarantee homogeneity since, firstly, data sets collected globally do not necessarily guarantee a spatially constant quality and, secondly, the adequacy of a particular modeling approach varies greatly depending on the available information and the tectonic context.

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. (2019). 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 (Styron and Pagani, 2019) were produced. The latter in particular expands on the work formerly done within the Faulted Earth project (Christophersen et al., 2015) and 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 from 2009 to 2014 (Pagani et al., 2015), were key for the development of hazard models in areas where GEM was unable to form collaborations with local institutions.

In this paper, we describe the criteria used to compile the GEM hazard mosaic. We discuss the main characteristics of the included models, and the procedure used to construct a global homogenized map. Finally, we compare properties of the computed hazard map to previously released models.

THE CRITERIA USED TO COMPILE THE GEM MOSAIC

The mosaic is built upon the GEM principle of openness, and so the primary condition for including a model is the ability for GEM to openly share it. Given the commitment to achieve a first global coverage by the end of 2018, we compiled the GEM mosaic following selection criteria with a balance between pragmatism and GEM's principles of collaboration, openness, and transparency.

In order to efficiently achieve this goal, we selected a model for each region using a three-tier approach. 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; therefore, Tier 1 represents what we consider the ideal case. The selected Tier 1 models include several national models, such as the 2014 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., Submitted). Many of the regional models are also Tier 1, including the SHARE project in Europe (Woessner et al., 2015) and the EMME 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 GEM-promoted projects 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. 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.

The hazard inputs for all models included in the mosaic use the standard format of the OpenQuake-engine (Pagani et al., 2014). This consists of at minimum three components: two logic trees describing epistemic uncertainty in the seismic source characterization (SSC) and in the ground motion characterization (GMC), and at least one seismic source model (SSM). A SSM is a list of sources accounting for all possible seismicity of engineering importance in the proximity of the investigated area; individual sources in the SSM only consider aleatory uncertainty. The GMC consists of weighted ground motion models (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 implicit modeling decisions inherent to the original software. This is possible because of the OpenQuake-engine's flexible framework. For example, we followed this approach to incorporate various models produced by the United States Geological Survey (USGS), as well as the national hazard model for Japan.

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

THE COMPONENTS OF THE GEM MOSAIC AND THEIR GENERAL CHARACTERISTICS

The GEM Mosaic is a collection of 30 Probabilistic Seismic Hazard Analysis (PSHA) input models designed to compute seismic hazard at large scales (Table 1 and Figure 1). Fourteen are national or sub-national models, while the remaining are regional models. The oldest included model is the USGS Hawaii model (Klein et al., 2001); all the other models were published after 2007. Overall, the GEM mosaic contains about 3.5 million earthquake sources that generate around 1.8 billion ruptures. The GMC includes about 90 ground-motion prediction equations subdivided into various tectonic regions (e.g. Active Shallow Crust, Stable Continental Crust). Here, we describe each of the models included in the GEM Mosaic, covering the globe by geographic region. Rather than providing a homogenous 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.

NORTH AMERICA

Six models were used to compute hazard in North America. From north to south, these include: the 2007 USGS Alaska model (Wesson et al., 2007, 2008); the 2015 Canada national hazard model produced by Natural Resources Canada (Adams et al., 2015); the 2014 USGS National Seismic Hazard Model (Petersen et al., 2014) in combination with version 3 of the Unified California Earthquake Rupture Forecast (UCERF3, Field et al. (2014)); a seismic hazard model for Mexico developed by GEM; and the regional hazard model covering Central America and the Caribbean, prepared in the framework of the CCARA project.

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

Table 1. Components of the GEM Mosaic

Acr.	Year	Region covered	Tier	Project	Reference publications
ALS	2007	Alaska	1		Wesson et al. (2007, 2008)
ARB	2018	Arabian Peninsula	1		Zahran et al. (2015, 2016)
AUS	2018	Australia	1		Allen et al. (Submitted)
CAN	2015	Canada	1		Adams et al. (2015)
CCA	2018	Caribbean, C. America	1	CCARA	
CEA	2018	Central Asia	1	EMCA	Ullah et al. (2015)
CHN	2015	China	1		Gao (2015)
EUR	2013	Europe	1	SHARE	Woessner et al. (2015)
HAW	1998	Hawaii	1		Klein et al. (2001)
IDN	2017	Indonesia	1		Irsyam et al. (Submitted)
IND	2012	India and surroundings	2		Nath and Thingbaijam (2012)
JPN	2014	Japan	1		HERP (2014)
KOR	2018	Korean Peninsula	3		Gao (2015), HERP (2014)
MEX	2018	Mexico	3		
MIE	2016	Middle-East	1	EMME	Danciu et al. (2017, 2018); Seşetyan et al. (2018)
NAF	2018	Northern Africa	3		Poggi et al. (2019)
NEA	2018	Northeastern Asia	3		
NWA	2018	Northwestern Asia	3		
NZL	2010	New Zealand	1		Stirling et al. (2012)
PHL	2018	Philippines	3		Penarubia et al. (Submitted)
PAC	2018	Pacific Islands	3		Johnson and Pagani (in prep.)
PNG	2015	Papua New Guinea	1		Ghasemi et al. (2016)
SAM	2018	South America	1	SARA	Garcia et al. (2017)
SEA	2018	Southeast Asia	1		Ornthammarath et al. (Submitted)
SSA	2018	Sub-Saharan Africa	1	SSAHARA	Poggi et al. (2017)
TEM	2015	Taiwan	1		Wang et al. (2016)
UCF	2014	California	1		Field et al. (2014)
USA	2014	Conterminous U.S.	1		Petersen et al. (2015)
WAF	2018	Western Africa	3		
ZAF	2018	South Africa	1		Midzi et al. (2019)

of smoothed seismicity and fault sources, while subduction earthquakes are separated into interface earthquakes generated by fault sources with a 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, for the first time, a probabilistic computation of hazard generated by the Cascadia subduction zone. The SSC is organized into four quadrants: two covering the eastern and western Arctic regions, one comprising British Colombia and part of the West, and one incorporating Ontario, Quebec, and Atlantic Canada. The 2015 Canada model is, to our knowledge, the first national hazard model accounting for epistemic uncertainty in the ground motion model via the backbone approach (Atkinson and Adams, 2013).

The 2014 USGS National Seismic Hazard Model for the Conterminous United States utilized in the GEM mosaic includes two hazard models. The 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, including a specific calculator for the UCERF3 model, and extended classical and event-based calculators that consider the cluster model in the New Madrid Fault Zone (Petersen et al., 2008, 2014). The implementation of the UCERF3 model was particularly challenging, as it required adding to the OpenQuake-engine the ability to compute hazard from seismic source models with a peculiar structure (Field et al., 2014). Specifically, these adaptations enabled the software to build the earthquake rupture forecast directly from the input file, thus adding the ability to incorporate rupture configurations that would not normally be supported by common parametric definitions of earthquake sources.

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 consists of sets of GMMs for each of the four tectonic regions considered. The selection of GMMs was performed using residual analysis of strong ground-motion data for a set of candidate GMMs. The strong-motion data was provided by the National Autonomous University of Mexico (UNAM,

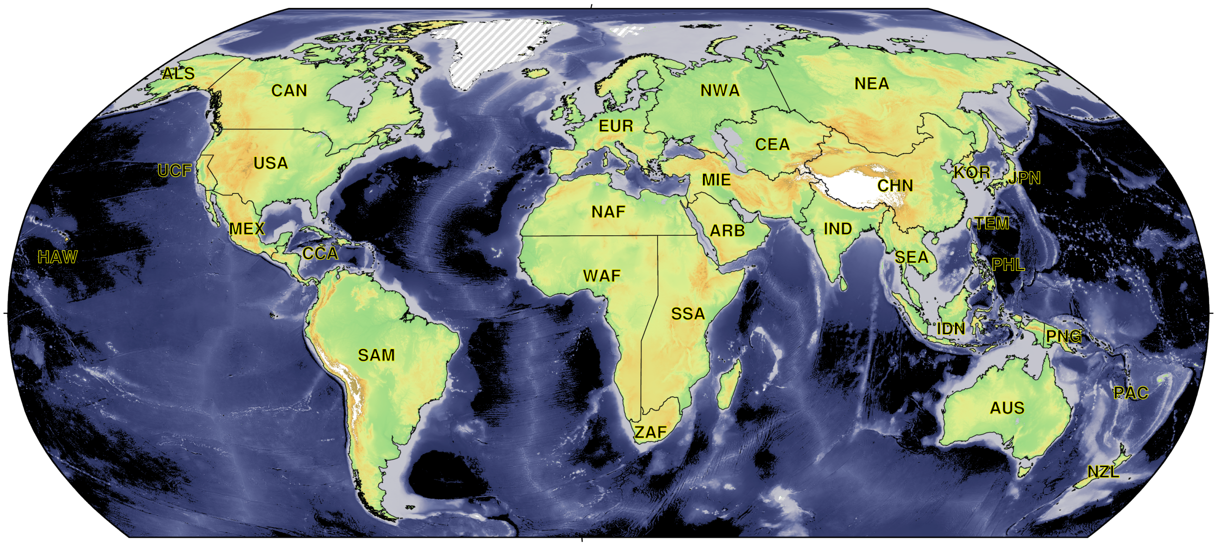

Figure 1. Geographic coverage of the models included in the GEM mosaic (version 2018.1).

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 a[illegible] was developed for the CCARA project, which was the first active fault dataset mapped by GEM for the GEM Global Active Faults database; this regional database served as the template for the global database (Styron et al., 2018a). As with the Mexico model, we completed the GMC via a residual analysis on a local strong-motion database containing recordings from both the Caribbean and Central America. Data from the Lesser Antilles was retrieved from the Engineering Strong-Motion database (ESM, https://esm.mi.ingv.it), while the Ministerio de Medio Ambiente y Recursos Naturales (MARN, http://m.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 source model 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. 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) contains a set of GMMs for each tectonic region, selected using an extensive residual analysis performed on an database of strong-motion recordings collected for several countries in the region, including 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 SHARE model Woessner et al. (2015) was selected for calculating seismic hazard in Europe. The SHARE project - funded by the European Union under the Seventh Framework Programme (FP7) was the first GEM regional project, 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 SHARE SSC is composed of three source models developed with different initial data sets and modeling strategies. 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 (Delavaud et al., 2012). 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., 2019) was built by the GEM Hazard Team using an earthquake catalog covering the entire region and new database of shallow active faults (Styron and Poggi, 2018) compiled as part of the construction of GEM's Global Active Fault database. The SSC consists of two source models: one which includes both smoothed seismicity and fault sources with simple geometry, and a second containing only smoothed seismicity. In the latter, epistemic uncertainty for the seismicity rates is considered.

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, see Poggi et al. (2017)). The model includes smoothed seismicity within source zones with geometries mostly 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 is particularly uncertain in this region—and more generally in Africa—given the complete absence of strong-motion recordings. The GMC contains a logic tree with five tectonic regions allowing a transition from pure active shallow crust to a stable continental region through a weighted combination of models normally assigned to these two classes.

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 using primarily information taken from literature (Poggi, 2019). One of the most prominent earthquake sources in this model, located in Ghana, is probably related to fault structures within the Western African Shield (Amponsah, 2004).

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. Because of the low level of seismicity and limited data, the SSC is inherently uncertain, and so the authors incorporate alternative Gutenberg-Richter, maximum magnitude, and depth values to account for epistemic uncertainty (discussed more in Section 4).

ASIA

Asia is the most complex continent in terms of both the number of hazard models included in the GEM Mosaic as well as their seismotectonic diversity. We describe the main characteristics of the thirteen models chosen, going from West to East. The westernmost coverage of Asia is the Earthquake Model for the Middle East (EMME; (Seşetyan et al., 2018)), which extends from the western coast of Turkey to Afghanistan and Pakistan. This model includes the Caucasian countries (Georgia, Armenia and Azerbaijan), Iran, and countries in the Middle East bordering 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 catalogue (Zare et al., 2014), an active fault database (Danciu et al., 2017) and a strong-motion database (Danciu et al., 2018). The EMME SSC contains two seismic source models (Danciu et al., 2017). The first uses area sources to model active shallow crustal seismicity, shallow stable crustal seismicity, and subduction intraslab seismicity in combination with fault sources producing interface ruptures in the Makran subduction region. The second model accounts for distributed seismicity using a grid of points with rates obtained from a seismicity smoothing process.

The model for the Arabian Peninsula (Zahran et al., 2015, 2016) was developed by the Saudi Geological Survey (SGS), and implemented into the OpenQuake-engine within a collaboration between GEM and SGS. Volcanic activity in the proximity of the Red Sea poses particular challenges to hazard modeling in this region, because it controls the location of some of the earthquake sources as well as the attenuation of seismic waves within the crust.

The Earthquake Model for Central Asia (EMCA; Ullah et al. (2015)) covers Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, and Kazakhstan. The model was developed within a project lead by the GeoForschungsZentrum (GFZ) in Potsdam, Germany. The SSC consists of a single seismic source model containing only area sources, while the GMC contains one set of GMMs for active shallow crustal sources and one single GMM for stable continental crust. 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.

We compute hazard in the Northern part of Asia using two models that together cover the entire Russian territory, split around the 76°E meridian. In the Northwestern Asia model (NWA), seismicity mostly occurs within cratonic and stable crust, spanning an area of low seismic hazard. The Northeastern Asia model (NEA) covers Mongolia and the eastern part of Russia. The seismic source model 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).

We implemented the most recent national seismic hazard model for China (Gao, 2015) 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. The GMC contains four GMMs: one per tectonic region covered by this model.

For Taiwan, we used the most recent model version produced by the Taiwan Earthquake Model (Wang et al., 2016), one of the public organizations supporting GEM. The SSC for this hazard model contains a single seismic source model, based on 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.

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 Headquarters for Earthquake Research Promotion (HERP) into the OpenQuake-engine format. This model is unique in that the SSC includes mutually exclusive ruptures on some subduction interface faults, an aspect that required the addition of some computational features to the OpenQuake-engine. For example, the largest interface earthquakes in the Nankai subduction are modeled using this approach which in the investigation timeframe (i.e. 30 or 50 years) admits only the occurrence of a large event. The GMC uses a single GMM for each tectonic region.

Although no national model for the Korean Peninsula was available, coverage was obtained by merging sources from both the China and Japan national model. The model is a combination of area sources from the China national model, which model shallow seismicity, and subduction sources from the Japan national model. For the GMC, we used primarily 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. The SSC for this model accounts for epistemic uncertainty in an unequally weighted logic tree of three seismic source models: one comprising of area sources, and two using smoothed seismicity but adopting different minimum magnitudes. The GMC uses a set of GMMs for each modeled tectonic region, and 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).

For Southeast Asia, the Earth Observatory of Singapore and Mahidol University developed two seismic source models, which are combined to create the SSC for this region (Ornthammarath et al., Submitted). The two source models were developed independently and are weighted equally in the logic tree. A single GMC is used for both seismic source models, which uses a set of GMMs for each of the three tectonic region types within the GEM Mosaic coverage by this model (active shallow crust, subduction interface, and subduction intraslab).

The Philippines is covered by a national PSHA model developed in the by a scientific collaboration between GEM and the Philippine Institute of Volcanology and Seismology (PHIVOLCS) (Penarubia et al., Submitted), which aimed to expand upon previous work done by PHIVOLCS. The SSC follows the approach used for the South America, Caribbean and Central America, and Mexico models. The seismic source model includes a fault database derived from the

PHIVOLCS compilation used in 2017, but with updated fault characteristics. The GMC uses a set of GMMs for each tectonic region, where the crustal GMM set is based partly on residual analysis.

The GEM 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.

The Australia model was released in 2018 (Allen et al., Submitted) and represents the latest model produced by Geoscience Australia. The SSC includes a logic tree with twenty independently developed seismic source models 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 source models 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., the outcome of an effort involving a pool of organizations led by GNS Science. The SSC includes distributed seismicity and faults 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 a single GMM for each tectonic region.

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 branches: one consisting solely of smoothed seismicity, and a second that combines complex faults and area sources. The GMC is based partly on residual analysis performed in an earlier study by Petersen et al. (2012).

Because seismic source modeling is particularly challenging in Hawaii, where most seismicity is controlled by volcanism, few recent studies have modeled the seismic hazard of the Hawaiian Island. We chose to include the model of Klein et al. (2001) in the GEM Mosaic. The SSC includes a number of formerly activated faults with complex geometry along volcanic flanks on Hawaii Island, and both area and smoothed seismicity sources capturing the distributed seismicity. GMC is also complicated for this island chain, given the peculiar attenuation characteristics in the volcanic area and the limited number of strong-motion recordings available.

Finally, the hazard model for the Pacific Islands (Johnson and Pagani, in prep.) was developed by the GEM Hazard Team following a scheme similar to that described for the models of Mexico, the Caribbean and Central America, South America, and the Philippines. The model adopts the GMC used for neighboring Papua New Guinea.

A SUMMARY OF THE MAIN CHARACTERISTICS OF MODELS IN THE GEM MOSAIC

Overall, the described set of PSHA models provides a comprehensive summary of probabilistic seismic hazard analyses 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.

The input format for the OpenQuake-engine contains two logic tree structures accounting for epistemic uncertainty in the SSC and GMC, respectively. 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 taken into account by defining a set of GMMs for each tectonic region considered in the logic tree. The only exception to this standard approach is the ground motion 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 included models, the use of epistemic uncertainty in the SSC is more variable. Thirteen models incorporate this type of uncertainty, mainly by defining alternative seismic source models 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 seismic source models is the latest national hazard model for Australia (Allen et al., Submitted), which contains 18 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 also implemented in the OpenQuake-engine and included in the mosaic, but with their SSMs in a collapsed form in order to reduce calculation complexity.

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; twenty models include this source typology. Most of the models without fault sources are located in stable areas where identifying active structures is in general more challenging. Overall (but excluding sources in the UCERF3 model) the GEM mosaic contains more than 25,000 fault sources of simple and characteristic typologies, using the OpenQuake-engine terminology.

In the subduction areas, common practice in the GEM Mosaic suite of models is to separate the sources accounting for subduction interface versus intraslab seismicity. Interface sources, given their variability in geometry, are 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 model inslab seismicity using faults (e.g. Taiwan model), some use area sources with different hypocentral depths, and some model inslab seismicity with 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 in terms of the geographic distribution of the peak ground acceleration (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 760-800 m/s in the uppermost 30 meters, a range which represents rock conditions according to commonly used site classification schemes. 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 contiguous area exhibiting moderate to high values of seismic hazard.

Since the GEM mosaic contains a variety of models created using different approaches and methodologies, the hazard results at the border between models will 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.

HOMOGENIZATION OF HAZARD CURVES

The methodology adopted for combining the hazard computed with the models in the GEM mosaic relies on a reference global grid of points used to calculate results. The geometry of this grid can have different characteristics; we chose a grid that is (almost) equally spaced in distance. Every model has a corresponding computation area (Figure 1) used to extract a subset of points - which we call ,“sites” - from the global grid. We use a buffer of about 75 km around each computation area in order to have a sufficiently large band of overlapping sites across each border between adjacent models.

Notably, from a purely scientific perspective, the hazard map obtained through this homogenization 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. The methodology described herein—with minor modifications—can be used to thoroughly study these differences.

In order to obtain global homogenized hazard maps, we sequentially analyze every model and store the corresponding hazard curve for each site in either a final repository if the site is inside the model, or in temporary repository if the site is within one of the buffer regions. In a second phase, we further process the hazard curves for sites located within the buffer between models. In most of the cases, sites within a buffer region have two hazard curves, one for each model across which the buffer is placed. For a minor number of sites concentrated in Asia, there are more than two hazard curves assigned. This occurs, for example, near the contact between the models of China, Central Asia, the Middle East, and India.

The homogenization of hazard curves is completed by processing each point included 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. For hazard curves at sites occupying the computation area of the model, we assign an initial weight equal to the sum of the buffer distance and d_b. On the contrary, for the hazard curves of sites within the buffer region but outside the computation area of the model, the initial weight is equal to the difference between the buffer distance and d_b. Weights are subsequently normalized by their sum, used to compute the contribution of each hazard curve, and collocated curves are summed to yield the final homogenized curve. For a given site, each ordinate of the hazard curve is obtained as follows:

$$poe_{iml} = poe_{iml}^{inside} * w^{inside} + poe_{iml}^{outside} * w^{outside} \quad (1)$$

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 PGA with 10% Probability of Exceedance (PoE) in 50 years.

We discuss this appraisal using the maps in Figure 3. Each map contains areas filled with three colors which indicate the following: Given a reference ground-motion threshold (gm_T), for example 0.1 g, 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 3A shows the map obtained for a gm_T equal to 0.1g. Overall, the two maps exhibit compatible results. 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 3B, the gm_T is increased to 0.3 g, 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 generally higher values of hazard compared to the ones in 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, and Indonesia. On a coarser scale, we note that the GEM map tends to concentrate high hazard areas along major subduction regions, whereas the GSHAP model puts more hazard along the Alpine-Himalayan orogenic belt.

The trend just described is substantiated by the map in Figure 3C, computed for a gm_T of 0.5 g. 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 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 are mostly concentrated in Asia (China, Hindu Kush and Kamchatka).

CONCLUSIONS

The GEM hazard map and the GEM 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 GEM mosaic is a comprehensive summary of the most recent publicly accessible hazard input models developed at national and regional scale produced globally over the last ten years.

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, 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 highlights sections of the Alpine-Himalayan orogenic belt.

We hope that the GEM mosaic will promote a collaborative, bottom-up approach to the construction of more homogenous seismic hazard models, notwithstanding the difficulty of properly defining what exactly represents a set of homogenous hazard models. In our opinion, the degree of homogeneity between the SSC in two different hazard input models must be analyzed by taking into account 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 GEM mosaic offers a number of scientific opportunities, and renders 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 GEM 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. Additional research 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.

The GEM Mosaic is built upon a dynamic framework, in which the database of models will be maintained to include the most up-to-date openly available hazard information. This framework 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 paper. In the future, GEM aims to incorporate updates of existing models and to expand the number of national 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.

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*.

Allen, T. I., Griffin, J., Leonard, M., Clark, D., and Ghasemi, H., Submitted. The 2018 National Seismic Hazard Assessment of Australia: Quantifying Hazard Changes And Model Uncertainties. *Earthquake Spectra* .

Amponsah, P. E., 2004. Seismic activity in Ghana: past, present and future. *Annals of Geophysics* **47**. doi:10.4401/ag-3319.

Atkinson, G. M. 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. doi: https://doi.org/10.1139/cjce-2012-0544.

Atkinson, G. M., Bommer, J. J., and Abrahamson, N. A., 2014. Alternative Approaches to Modeling Epistemic Uncertainty in Ground Motions in Probabilistic Seismic-Hazard Analysis. *Seismological Research Letters* **85**, 1141–1144. doi:10.1785/0220140120.

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. doi:10.1093/gji/ggy005.

Christophersen, A., Litchfield, N., Berryman, K., Thomas, R., Basili, R., Wallace, L., Ries, W., Hayes, G. P., Haller, K. M., Yoshioka, T., Koehler, R. D., Clark, D., Wolfson-Schwehr, M., Boettcher, M. S., Villamor, P., Horspool, N., Ornthammarath, T., Zuñiga, R., Langridge, R. M., Stirling, M. W., Goded, T., Costa, C., and Yeats, R., 2015. Development of the Global Earthquake Model's neotectonic fault database. *Natural Hazards* **79**, 111–135. doi:10.1007/s11069-015-1831-6.

Danciu, L., Kale, O., and Akkar, S., 2018. The 2014 Earthquake Model of the Middle East: ground motion model and uncertainties. *Bulletin of Earthquake Engineering* pp. 1–37. doi:10.1007/s10518-016-9989-1.

Danciu, L., Şeşetyan, K., Demircioglu, M., Gülen, L., Zare, M., Basili, R., Elias, A., Adamia, S., Tsereteli, N., Yalçın, H., Utkucu, M., Khan, M. A., Sayab, M., Hessami, K., Rovida, A. N., 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., 2017. The 2014 Earthquake Model of the Middle East: seismogenic sources. *Bulletin of Earthquake Engineering* pp. 1–32. doi: 10.1007/s10518-017-0096-8.

Delavaud, E., Cotton, F., Akkar, S., Scherbaum, F., Danciu, L., Beauval, C., Drouet, S., Douglas, J., Basili, R., Sandikkaya, M. A., Segou, M., Faccioli, E., and Theodoulidis, N., 2012. Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe. *Journal of Seismology* **16**, 451–473. doi:10.1007/s10950-012-9281-z.

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**. doi: 10.4401/ag-3787.

Drouet, S., Montalva, G., Dimaté, M. C., Castillo, L. F., and Fernandez, G. A., 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*.

Field, E. H., Arrowsmith, R. J., Biasi, G. P., Bird, P., Dawson, T. E., Felzer, K. R., Jackson, D. D., Johnson, K. M., Jordan, T. H., Madden, C., Michael, A. J., Milner, K. R., Page, M. T., Parsons, T., Powers, P. M., Shaw, B. E., Thatcher, W. R., Weldon, R. J., 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. doi:10.1785/0120130164.

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

Garcia, J., Weatherill, G. W., Pagani, M., Rodriguez, L., 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*.

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. doi:10.1007/s11069-015-2117-8.

Giardini, D., Grünthal, G., Shedlock, K. M., and Zhang, P., 1999. The GSHAP global seismic hazard map. *Annali di Geofisica* **42**, 1225–1230.

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*. *Tech. rep.*, Headquarters for Earthquake Research Promotion. (in Japanese).

HERP, 2014. *The National Seismic Hazard Map 2014 Version—With an Overview on the Ground Motion Hazard of the Whole Country*. *Tech. rep.*, Headquarters for Earthquake Research Promotion. (in Japanese).

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. doi:10.1093/gji/ggu186.

Irsyam, M., Cummins, P., Faisal, L., Natawidjaja, D. H., Widiyantoro, S., Meilano, I., Triyoso, W., Rudiyanto, A., Hidayati, S., Ridwan, M., and Hanifa, R., Submitted. Development of the 2017 National Seismic Hazard Maps of Indonesia. *Earthquake Spectra* .

Johnson, K. and Pagani, M., in prep. Seismic Hazard Model For the Pacific Islands. *In preparation* .

Klein, F. W., Frankel, A. D., Mueller, C. S., Wesson, R. L., and Okubo, P. G., 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. doi:10.1785/0120000060.

Midzi, V., Manzunzu, B., Mulabisana, T., Zulu, B. S., Pule, T., Myendeki, S., and Rathod, G. W., 2019. The Probabilistic Seismic Hazard Assessment of South Africa. *Journal of Seismology* .

Nath, S. K. and Thingbaijam, K. K. S., 2012. Probabilistic Seismic Hazard Assessment of India. *Seismological Research Letters* **83**, 135–149. doi:10.1785/gssrl.83.1.135.

Ordaz, M. G., Cardona, O.-D., Salgado-Gálvez, M. A., Bernal-Granados, G. A., Singh, S. K., and Zuloaga-Romero, D., 2014. Probabilistic seismic hazard assessment at global level. *International Journal of Disaster Risk Reduction* **10**, 419–427. doi:10.1016/j.ijdrr.2014.05.004.

Ornthammarath, T., Warnitchai, P., Chan, C.-H., Wang, Y., Shi, X., Nguyen, P. H., Nguyen, J. M., Kosuwan, S., Thant, M., and Sieh, K., Submitted. Probabilistic Seismic Hazard Assessments for Northern Southeast Asia (Indochina): Smooth Seismicity Approach. *Earthquake Spectra* .

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**. doi:10.4401/ag-6677.

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-HAZARD-MAP-2018.

Pagani, M., Hao, K. X., 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. doi:10.1785/0220160101.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., and Vigano, D., 2014. OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismological Research Letters* **85**, 692–702. doi:10.1785/0220130087.

Penarubia, H., Johnson, K. L., Styron, R. H., Bacolcol, T. C., Bonita, J. D., Narag, I. C., Perez, J. S., Sevilla, W. I. G., Solidum Jr., R. G., Pagani, M., and Allen, T. I., Submitted. Probabilistic Seismic Hazard Analsyis model for the Philippines. *Earthquake Spectra* .

Petersen, M., Moschetti, M., Powers, P., Mueller, C., Haller, K. M., Frankel, A., Zeng, Y., Rezaeian, S., Harmsen, S., Boyd, O., Field, E., Chen, R., Rukstales, K., Luco, N., Wheeler, R., Williams, R., and Olsen, A., 2014. *Documentation for the 2014 update of the United States national seismic hazard maps*. *Open-File Report 2014–1091*, U.S. Geological Survey.

Petersen, M. D., 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. doi:10.1016/j.tecto.2004.03.026.

Petersen, M. D., Frankel, A. D., Harmsen, S. C., Mueller, C. S., Haller, K. M., Wheeler, R. L., Wesson, R. L., Zeng, Y., Boyd, O. S., Perkins, D. M. et al., 2008. *Documentation for the 2008 update of the United States national seismic hazard maps*. *Tech. rep.*, Geological Survey (US).

Petersen, M. D., Harmsen, S. C., Rukstales, K. S., Mueller, C. S., McNamara, D. E., Luco, N., and Walling, M., 2012. *Seismic Hazard of American Samoa and Neighboring South Pacific Islands–methods, Data, Parameters, and Results*. US Department of the Interior, US Geological Survey.

Petersen, M. D., Moschetti, M. P., Powers, P. M., Mueller, C. S., Haller, K. M., Frankel, A. D., Zeng, Y., Rezaeian, S., Harmsen, S. C., Boyd, O. S. et al., 2015. The 2014 United States national seismic hazard model. *Earthquake Spectra* **31**, S1–S30.

Petersen, M. D., Mueller, C. S., Moschetti, M. P., Hoover, S. M., Rukstales, K. S., McNamara, D. E., Williams, R. A., Shumway, A. M., Powers, P. M., Earle, P. S. et al., 2018. 2018 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes. *Seismological Research Letters* **89**, 1049–1061.

Poggi, V., 2019. Seismic Hazard Model For Western Africa. *In preparation* .

Poggi, V., Durrheim, R., Tuluka, G. M., 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* pp. 1–31. doi:10.1007/s10518-017-0152-4.

Poggi, V., Styron, R., and Garcia-Pelaez, J., 2019. Seismic Hazard Model For Northern Africa. *In preparation* .

Seşetyan, K., Danciu, L., Demircioğlu Tümsa, M. B., Giardini, D., Erdik, M., Akkar, S., Gülen, L., 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, M. A., Mammadli, T., Al-Qaryouti, M., Sayab, M., Tsereteli, N., Utkucu, M., Varazanashvili, O., Waseem, M., Yalçın, H., and Yılmaz, M. T., 2018. The 2014 seismic hazard model of the Middle East: overview and results. *Bulletin of Earthquake Engineering* **16**, 3535–3566. doi:10.1007/s10518-018-0346-4.

Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., Martins, L., Pagani, M., Rao, A., Simionato, M., Viganò, D., Yepes-Strada, C., Acevedo, A., Crowley, H., Horspool, N., Jaiswal, K., Journeay, M., and Pittore, M., 2019. Development of a Global Seismic Risk Model. *Earthquake Spectra* .

Stewart, J. P., Douglas, J., Javanbarg, M., Bozorgnia, Y., Abrahamson, N. A., Boore, D. M., Campbell, K. W., Delavaud, E., Erdik, M., and Stafford, P. J., 2013. Selection of Ground Motion Prediction Equations for the Global Earthquake Model. *Earthquake Spectra* **31**, 19–45. doi: 10.1193/013013EQS017M.

Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Dissen, R. V., 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. doi:10.1785/0120110170.

Styron, R., Garcia-Pelaez, J., and Pagani, M., . CCAF-DB: The Caribbean and Central American Active Fault Database. *Natural Hazards and Earth System Science* Submitted.

Styron, R., García-Pelaez, J., and Pagani, M., 2018a. GEM Central America and Caribbean Active Faults Database. doi:10.13117/CENTRAL-AMERICA-CARIBBEAN-ACTIVE-FAULTS.

Styron, R. and Pagani, M., 2019. The GEM Global Active Faults Database (GAF-DB). *Earthquake Spectra* .

Styron, R. and Poggi, V., 2018. GEM North Africa Active Fault Database. doi:10.13117/N-AFRICA-ACTIVE-FAULTS.

Styron, R., Poggi, V., and Lunina, O. V., 2018b. GEM Northeastern Asia Active Fault Database. doi: 10.13117/NE-ASIA-ACTIVE-FAULTS.

Ullah, S., Bindi, D., Pilz, M., Danciu, L., Weatherill, G., Zuccolo, E., Ischuk, A., Mikhailova, N. N., Abdrakhmatov, K., and Parolai, S., 2015. Probabilistic seismic hazard assessment for Central Asia. *Annals of Geophysics* **58**. doi:10.4401/ag-6687.

Villegas, G. C., Mendoza, C., and Ferrari, L., 2017. Mexico Quaternary Fault Database. *Terra Digitalis* **1**, 1–9. doi:10.22201/igg.terradigitalis.2017.1.3.50.

Wang, Y.-J., Chan, C.-H., Lee, Y.-T., Ma, K.-F., Shyu, J. B. H., Rau, R.-J., Cheng, C.-T. et al., 2016. Probabilistic seismic hazard assessments for Taiwan. *Terr. Atmos. Ocean. Sci.* **27**, 325–340.

Weatherill, G. A. 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*, p. paper n. 1026. Istanbul.

Weatherill, G. A., 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. doi:10.1093/gji/ggw232.

Wesson, R. L., Boyd, O. S., Mueller, C. S., Bufe, C. G., Frankel, A. D., and Petersen, M. D., 2007. *Revision of time-independent probabilistic seismic hazard maps for Alaska*. *Tech. rep.*, Geological Survey (US).

Wesson, R. L., Boyd, O. S., Mueller, C. S., and Frankel, A. D., 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.

Woessner, J., Laurentiu, D., Giardini, D., Crowley, H., Cotton, F., Grünthal, G., Valensise, G., Arvidsson, R., Basili, R., Demircioglu, M. B. et al., 2015. The 2013 European seismic hazard model: key components and results. *Bulletin of Earthquake Engineering* **13**, 3553–3596.

Zahran, H. M., Sokolov, V., Roobol, M. J., Stewart, I. C., Youssef, S. E.-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, H. M., Sokolov, V., Youssef, S. E.-H., and Alraddadi, W. W., 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, M. B., Kalafat, D., Erdik, M., Giardini, D., Khan, M. A., and Tsereteli, N., 2014. Recent developments of the Middle East catalog. *Journal of Seismology* **18**, 749–772. doi:10.1007/s10950-014-9444-1.

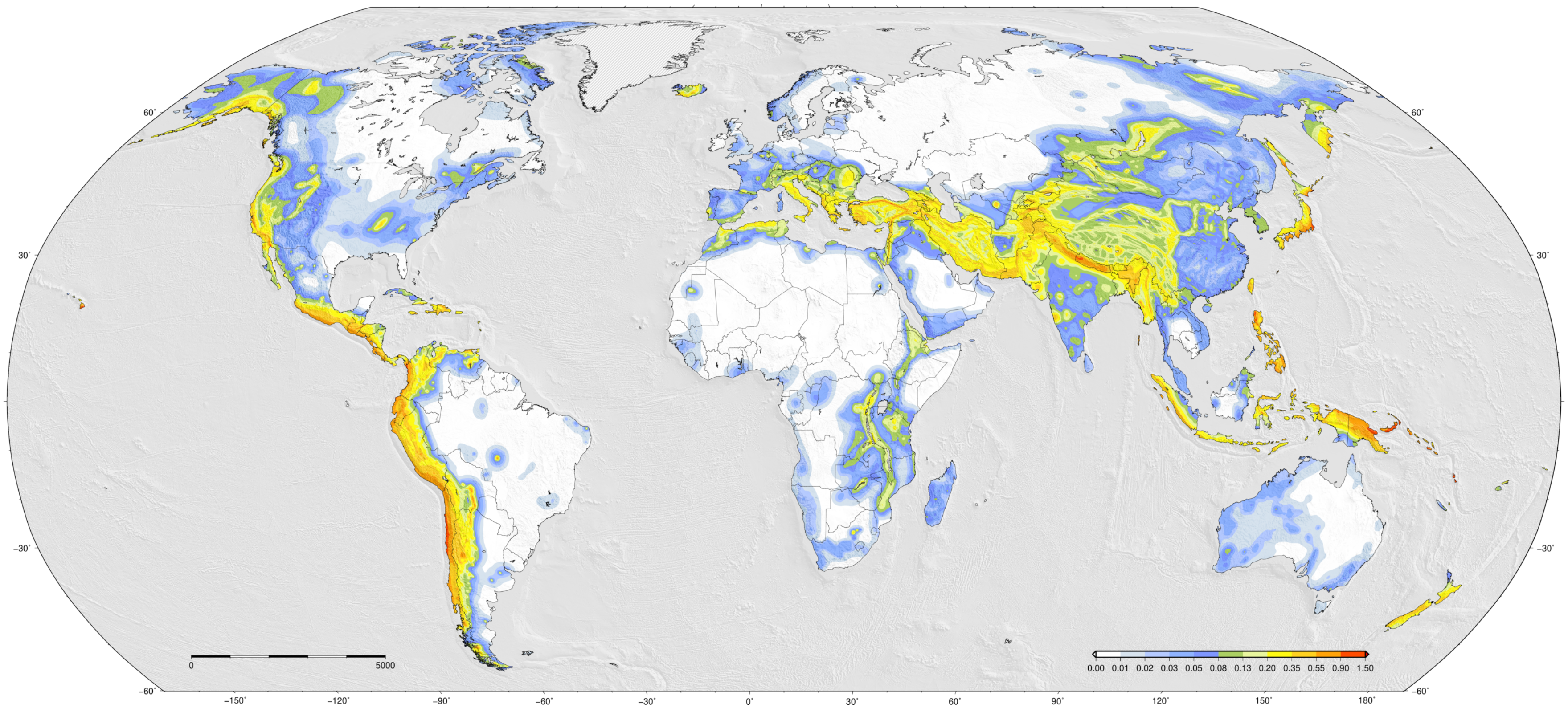

Figure 2. The GEM global hazard map (version 2018.1). The map displays Peak Ground Acceleration (PGA) with a 10% probability of being in exceeded in 50 years on reference soil conditions (Vs30=760-800m/s).

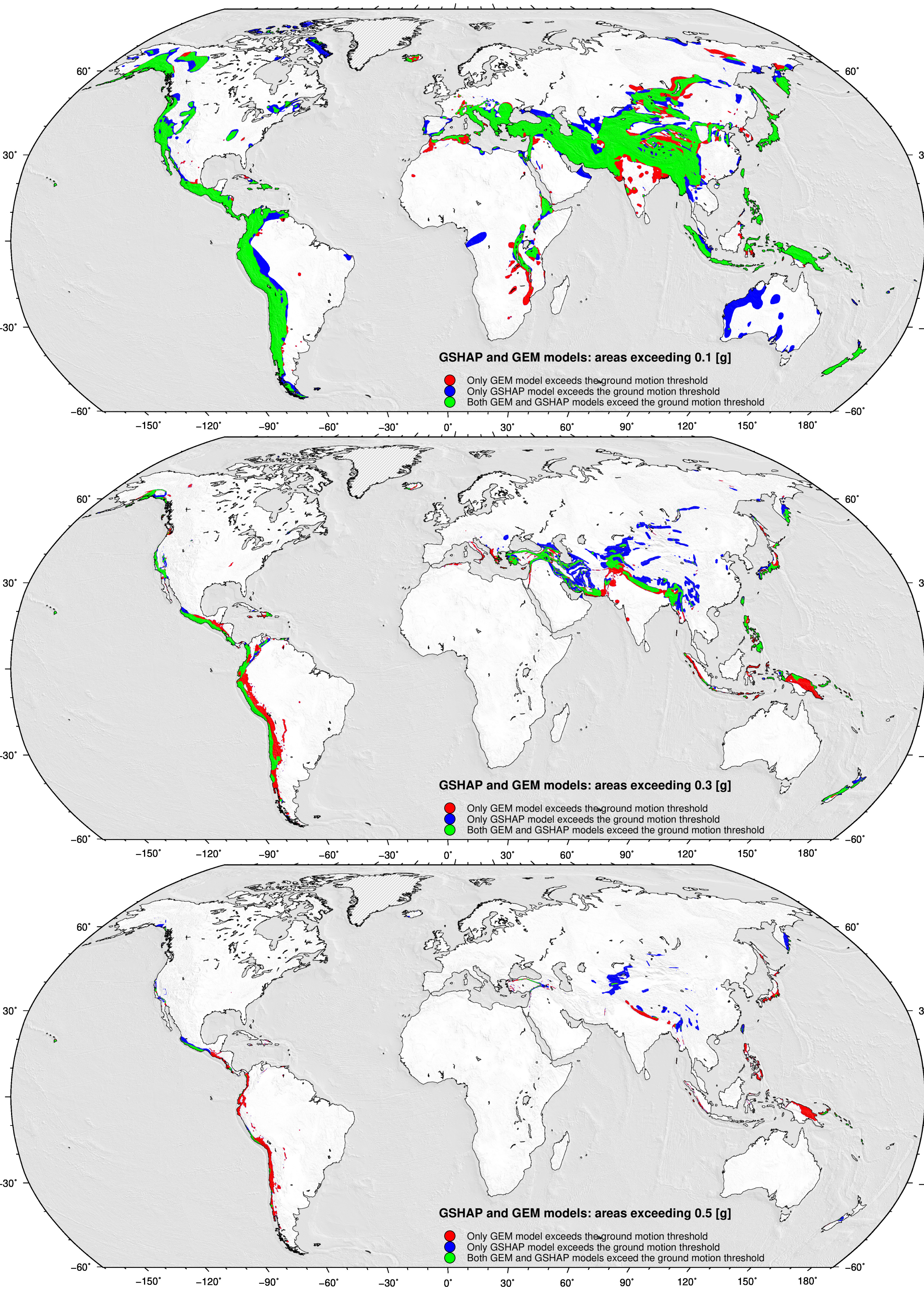

Figure 3. Maps comparing the pattern of hazard included in the GSHAP and GEM (version 2018.1) global hazard maps.