Appraising the PSHA Earthquake Source Models of Japan, New Zealand, and Taiwan

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ABSTRACT

Earthquake-hazard models are one of the major contributions provided by the seismological community to tangibly support disaster risk reduction policies at a national level. Although the societal impact of hazard analyses can be huge, the development of models remains a scientific activity developed within frameworks that have a strong national emphasis and partial international recognition. However, broad acceptability of hazard models is a key aspect for achieving authoritativeness and a prerequisite for warranting that their construction is completed using well-recognized methodologies.

As part of an enduring international collaboration between leading organizations operating in the hazard and risk fields in Japan, New Zealand, Taiwan, and the Global Earthquake Model initiative, we discuss the main characteristic of the earthquake source models—as implemented for the OpenQuake engine—used for the calculation of the most recent national seismic-hazard maps of these three countries. Particular emphasis is placed on comparing the various modeling options adopted in the different tectonic regions, on emphasizing commonalities, and on discussing the most controversial modeling solutions. Despite the many connections from a seismotectonic point of view between the three countries, the comparison highlights different modeling choices for the various tectonic regions, which constitute a spectrum of possible epistemic uncertainties, as well as modeling issues that could be collectively explored in future phases of this international collaboration.

INTRODUCTION

The availability of earthquake-hazard models is a key prerequisite for the definition of effective risk reduction policies at national level. The possible uses of the results provided by earthquake-hazard models are varied. Perhaps, their most common, convincing, and effective use is for the definition of actions for building codes and their use in a cost-effective design of the built environment. Currently, many developed countries regularly issue hazard models as an integral part of their system of policies for risk prevention and reduction enforced at the national level.

Owing to the complexity of the underlying natural phenomena, the preparation of earthquake-hazard models is a complex scientific exercise, which involves various sectors of the scientific community. Probabilistic seismic-hazard analysis (PSHA; Cornell, 1968; McGuire, 2004) is the methodology currently most widely adopted for the calculation of National Seismic Hazard Maps and is also the framework within which scientists cooperate and develop comprehensive interpretations of the earthquake process.

The preparation of national hazard models seldom follows formal standard approaches like the ones adopted in some engineering sectors (e.g., Senior Seismic Hazard Analysis Committee [SSHAC], 1997); however, the process is moving toward the comprehensive involvement of the scientific community. In a similar manner, methods used to demonstrate that the results provided match the minimal levels of quality assurance—which are commonly used in specialized hazard studies, for example, in the nuclear sector (Bommer et al., 2013)—observe increased adoption.

Nonetheless, in a majority of cases, each country follows a specific protocol for the construction of hazard models that fulfills national requisites and accounts for the various organizations involved in the process, going from the construction through to the application of the computed results. While understandable in a national perspective, this policy also hinders the possibility of making the process more transparent to the international community.

Considering the societal impact of seismic-hazard analyses, persistent scientific challenges increasingly emphasize the need for collaboration to make effective use of the knowledge collected by the various national organizations. Recognizing these challenges, the Global Earthquake Model (GEM) initiative since 2009 has invested resources to promote and support activities and projects aimed at stimulating international collaboration in the fields of earthquake hazard and risk. Other initiatives in the past, like the Global Seismic Hazard Assessment Program (Giardini et al., 1999) and, more recently, the SHARE project in Europe (Woessner et al., 2015), worked at promoting transnational harmonization of hazard models (for a comprehensive list, see references in Pagani et al., 2015). Within this framework, since 2014 experts from leading organizations in Japan, New Zealand, and Taiwan meet on a yearly basis to share their experiences and to discuss new methods for the development of national seismic-hazard models, Japan,
Taiwan, and New Zealand have all recently experienced strong and damaging earthquakes (e.g., 2011 M 6.3 Christchurch earthquake, 2011 M 9.1 Great East Japan earthquake, and 2016 M 6.6 Meinong, Taiwan, earthquake), which produced a wealth of new information and questions and reaffirmed the need for increased collaboration and discussion within the broader scientific community. In addition to this, the many commonalities the three countries share from a seismotectonic point of view, such as numerous fault structures onshore, large subduction sources offshore, as well as important volcanic belts as in the case of Japan and New Zealand, call for a more intensive international collaboration (Hao and Fujiwara, 2013).

This article provides a summary of the experiences collected in Japan, Taiwan, and New Zealand on national seismic-hazard mapping and offers a comparison of the main characteristics of the earthquake source models (ESMs) included in the most recent PSHA models for three of the most seismically active countries in the world. The versions of the hazard models considered are:

- The 2014 Japanese earthquake-hazard model (Fujiwara et al., 2009 [hereafter, JPN14]; HERP, 2014) released on the Japan Seismic Hazard Information Station (J-SHIS) website (see Data and Resources) in December 2014;
- The 2010 National Seismic Hazard Model (hereafter, NZL10) for New Zealand (Stirling et al., 2012);
- The Taiwan Earthquake Model (TEM) hazard model (Wang et al., 2016; hereafter, TWN15).

Figure 1 shows the original hazard maps computed using these three models; the map for Japan shows the peak ground velocity (PGV) with 10% probability of exceedance in 50 yrs, whereas the maps for New Zealand and Taiwan reflect the peak ground acceleration with 10% probability of exceedance in 50 yrs. The comparisons discussed hereafter refer to the implementation of the PSHA models used to compute these maps and currently implemented for the OpenQuake engine (Pagani et al., 2014). The NZL10 and JPN14 are preliminary OpenQuake-engine versions and contain minor differences compared to the original implementations, which, in a majority of cases, were introduced to adjust the original model to the data format supported by the OpenQuake engine and have little effect on our results.

This article is structured as follows. In the Introduction section, we provide a summary of the main characteristics of the three models, and we illustrate the general properties of the earthquake sources as represented in the OpenQuake engine. The Comparing Earthquake Source Models section is fully dedicated to discussing commonalities, differences, and interesting qualities of the three ESMs. The Discussion and Conclusions of the article focuses on the main results and on outlining potential directions for future research.

Seismic-Hazard Mapping in Japan, New Zealand, and Taiwan

The national seismic-hazard maps for Japan are issued by a governmental organization called the Headquarters for Earthquake Research Promotion (HERP). Since 2005, HERP has routinely released two typologies of hazard results: (1) probabilistic seismic-hazard maps and (2) scenario earthquake-shaking maps for specific seismic source faults. The PSHA model combines time-dependent, long-term evaluations of earthquake occurrence as well as a strong-motion model. The hazard results and the PSHA input model are disseminated through an integrated web-based system called J-SHIS that has also operated since 2005. The system manages various data in an integrated manner and provides access to detailed information on seismic-hazard results as well as access to a site characterization model rendered on a high-resolution mesh (with a 250 m spacing) and a deep subsurface velocity structure model.

The Japan National Seismic Hazard model is updated every year. The latest version of the Japanese National Seismic Hazard maps was released in June 2016. The 2014 version used in this work is a major revision prompted by the occurrence of the 2011 Great East Japan earthquake (Fujiwara et al., 2013; HERP, 2014). Central and municipal governments use the Japan National Seismic Hazard maps for defining disaster prevention policies. Finally, the dissemination of hazard results to individuals and public organizations contributes to raising awareness and offers important reference information after the occurrence of significant earthquakes.

The NZL10 model is the latest version of the New Zealand National Seismic Hazard Model (NZHM) and was created by a pool of scientists led by GNS Science (Stirling et al., 2012). This model is the fifth generation of PSHA models issued in New Zealand since 1985 (Matuschka et al., 1985). The NZHM forms the basis, among other things, for defining the national seismic-hazard zone factor maps for the current structural design standard for New Zealand (NZS 1170) and is used for site-specific hazard studies and for the calculation of losses at a regional and national level.

The TWN15 model is developed by the TEM project, a collaboration of Taiwanese scientists working on the development of a hazard and risk model and prompted by Taiwan’s participation to the GEM initiative. The analyzed model is the 2015 version of a model initially issued in 2014 (Wang et al., 2016). Cheng et al. (2007) published a previous hazard model for Taiwan, which was mainly used for the design and operation of critical facilities.

The TWN15 model represents the first hazard model publicly released in Taiwan. Discussions on regularly issuing updated versions of this model, as well as on the potential uses of the results computed in various contexts (e.g., national seismic code, urban planning), are currently ongoing.

Main Characteristics of the Analyzed Hazard Models

Earthquake sources in JPN14 are defined using the various typologies of earthquakes as a reference (e.g., large interplate earthquakes in northern Sanriku-Oki). Earthquake sources are classified according to three categories. Category I includes sources modeling subduction-zone earthquakes occurring on well-constrained faults like the Nankai trough interface and the 2011 Great East Japan earthquake. Category II includes sources describing the occurrence of subduction interplate
and intraplate earthquakes with relatively high rates of occurrence but which lack well-defined source faults, such as the large interplate earthquakes in northern Sanriku-Oki. Category III comprises all other shallow crustal earthquake sources both on- and offshore. This category also includes sources describing the occurrence of the following typologies of earthquakes: earthquakes not assigned to source faults, characteristic earthquakes occurring on major active fault zones, earthquakes occurring on active faults other than major active fault zones, and earthquakes occurring onshore for which active faults have not been specified. The seismic intensity that can be generated by earthquakes modeled in category III can reach $I_{\text{JMA}}$ 6 upper (modified Mercalli intensity $\geq X$).

The NZL10 model contains two source typologies: faults and point sources. The approach used for the construction of the NZL10 source model is similar to the one used proposed by Stirling et al. (2002). Faults are used to model the occurrence of the largest earthquakes, whereas distributed seismicity accounts for ruptures on unknown faults. The Taiwan PSHA model (Wang et al., 2016) has a structure quite similar to the NZL10 model, with the exception that distributed seismicity is modeled using area sources instead of gridded seismicity.

COMPARING EARTHQUAKE SOURCE MODELS

A PSHA input model is the combination of an ESM and a ground-motion model (GMM). The former describes the location and frequency of occurrence in a given time frame of earthquakes of engineering relevance for the investigated area, whereas the latter is used to compute the expected level of shaking at the sites of interest, given the occurrence of a rupture.

The ESM and the GMM are usually affected by large epistemic uncertainties that are synthesized into a logic-tree structure (Kulkarni et al., 1984) reflecting different interpretations of various components and modeling approaches.

The three PSHA input models here discussed do not incorporate epistemic uncertainties. It could be argued that for the estimation of the overall uncertainty of hazard results this is
probably not a limitation, because the uncertainty range obtained with national or regional hazard models intuitively cannot be lower than the one obtained using site-specific hazard analyses (and therefore it is somewhat illogical to develop complex logic trees for these types of analyses; see e.g., Douglas et al., 2014). However, the lack of a proper examination of epistemic uncertainties affecting the various methods and datasets utilized in the construction of the PSHA input model makes the mean results more sensitive to the specific choices adopted during the model building phase. This is an aspect that will require further consideration during the construction of updated versions of the models discussed here.

Source Modeling in the OpenQuake Engine

The OpenQuake engine offers various source typologies that can be used to accommodate different ESMs for the commonly considered tectonic regions in PSHA analysis. The source typologies available in the OpenQuake engine belong to two main categories: (1) parametric and (2) nonparametric. All the parametric sources are defined in terms of geometry, magnitude–frequency distribution (MFD), temporal occurrence model (currently the OpenQuake engine supports only the classical Poisson temporal occurrence model), and information required for the modeling of finite ruptures. The parametric sources include typologies for distributed seismicity models as well as fault sources with different characteristics. Nonparametric sources are described in terms of a list of ruptures, each one characterized by a vector specifying the probability of zero occurrences in the investigation time \( t \), one occurrence in \( t \), two occurrences in \( t \), and so on.

The three hazard models are represented using the OpenQuake-engine input file format (Pagani et al., 2014; Silva et al., 2014). The Taiwanese scientists involved in the TEM initiative natively developed their hazard model in the OpenQuake-engine format, whereas the NZL10 model is a translation from the original hazard model of Stirling et al. (2012) completed by collaborators at GNS Science. The version of the JPN14 model implemented in the OpenQuake engine is the result of an ongoing collaboration between scientists at the National Research Institute for Earth Science and Disaster Resilience and GEM scientists based at the GEM headquarters in Pavia, Italy. The three models contain almost all the typologies of sources currently supported by the OpenQuake engine. Table 1 provides a summary of the source typologies used in each ESM.

The JPN14 model includes some faults in active shallow crust (ASC) with a time-dependent behavior, which are modeled in the OpenQuake engine as nonparametric sources. Because some of the comparisons discussed in the following sections are performed in terms of the annual rate of occurrence, in some cases we transform the probability of occurrence within a time \( t \) into an equivalent annual rate of occurrence. This conversion is completed using the following formula:

\[
\lambda = \frac{-\ln(1 - P(n > 0|t))}{t},
\]

(see also Petersen et al., 2007), in which \( t \) is the investigation time (e.g., the next 50 yrs), and \( P(n > 0|t) \) is the probability of at least one occurrence within the investigation time. The equivalent rate obtained using this formula must be considered with caution. For example, in the case of the Nankai trough interface source, a mean recurrence interval of 88 yrs is used in combination with an aperiodicity coefficient of 0.22 and a time since the last event of 68 yrs to compute a probability of occurrence in the next 50 yrs of 0.92. The Poisson equivalent rate computed is 20 yrs (see Fig. 2a), which is clearly a rather short recurrence interval for large subduction earthquakes.

The OpenQuake engine offers various MFD types: a double-truncated Gutenberg–Richter (GR) distribution, a discrete incremental distribution, a hybrid characteristic model in the style of Youngs and Coppersmith (1985), and a completely arbitrary discrete distribution. The double-truncated GR is a parametric distribution defined by a minimum and a maximum magnitude \((M_{\text{min}} \text{ and } M_{\text{max}} \text{, respectively})\) and the \( a \)- and \( b \)-value of the GR distribution \((a_{\text{GR}} \text{ and } b_{\text{GR}} \text{, respectively})\). The hybrid characteristic model is specified by a minimum magnitude \((M_{\text{min}})\), the GR \( b \)-value \((b_{\text{GR}})\), the characteristic magnitude \((M_{\text{char}})\), and either the rate of occurrence for \(M_{\text{char}}\) or the total moment rate released \((M_s)\). The discrete incremental and the arbitrary distribution are discrete distributions defined by a set of occurrence rates for different magnitude values. In the case of the former, the values of magnitude are equally spaced, whereas in the latter, each rate is combined with a generic magnitude value. The discrete incremental and the arbitrary distribution provide the maximum flexibility because with these distributions it is possible to reproduce almost all the possible distributions—although in a discrete form.

Earthquake Rates in the Three Earthquake Source Models

To provide a compact description of the overall seismicity occurrence, we compute the MFD for each model by stacking the MFDs defined for the various sources included. This is a customary exercise done in the model preparation phases to verify the overall consistency of the ESM and the proximity between

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**Table 1**

<table>
<thead>
<tr>
<th>OpenQuake-Engine Source Typologies Included in Each of the Three Earthquake Source Models Analyzed</th>
<th>JPN14</th>
<th>NZL10</th>
<th>TWN15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid of point sources</td>
<td>×</td>
<td>×</td>
<td>-</td>
</tr>
<tr>
<td>Area sources</td>
<td>-</td>
<td>-</td>
<td>×</td>
</tr>
<tr>
<td>Simple fault sources</td>
<td>-</td>
<td>-</td>
<td>×</td>
</tr>
<tr>
<td>Complex fault sources</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gridded fault source</td>
<td>×</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Characteristic fault source</td>
<td>×</td>
<td>×</td>
<td>-</td>
</tr>
<tr>
<td>Nonparametric sources</td>
<td>×</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

JPN14, the 2014 Japanese earthquake-hazard model; NZL10, The 2010 National Seismic Hazard Model; TWN15, The Taiwan Earthquake Model (TEM) hazard model.
the predicted earthquake rates and the rates derived from past seismicity (Field et al., 2009; Stirling et al., 2012). The comparison qualitatively checks if past seismicity is a possible, and probable, case admitted by the earthquake-hazard model used for the calculation of hazard and whether or not the characteristics of the seismicity produced by the model contradict past observations. Because our focus is the main characteristics of each model, the model MFDs are used as a means to understand the relationship between the seismicity assigned to the various source categories included within each model.

Figure 2 shows the MFDs for the three models. In the NZL10 and TWN15 models, earthquake occurrence is controlled up to large magnitudes by seismicity within the ASC, whereas subduction interface sources host the largest earthquakes that can be generated by each model. In the case of the JPN14 model, the overall seismicity occurrence is primarily controlled by the subduction interface sources. The TWN15 and the NZL10 model generate on average about 10 earthquakes of magnitude greater than 5.0 per year, whereas the JPN14 model produces about 100.

Table 2 summarizes the range of magnitudes covered by the sources in each tectonic region of each source model. The minimum magnitude considered is generally equal to 5.0 with the exception of the subduction interface sources in the TWN15 and NZL10, for which the minimum magnitude considered is 7.5 and 7.1, respectively. The values of maximum magnitude in the different tectonic regions are less homog-

<table>
<thead>
<tr>
<th>Tectonic Region</th>
<th>Japan</th>
<th>New Zealand</th>
<th>Taiwan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active shallow crust</td>
<td>5.00–7.60</td>
<td>5.00–8.20</td>
<td>4.00–7.60</td>
</tr>
<tr>
<td>Subduction interface</td>
<td>5.00–9.10</td>
<td>7.10–9.00</td>
<td>7.50–8.00</td>
</tr>
<tr>
<td>Subduction inslab</td>
<td>5.00–8.30</td>
<td>5.00–7.20</td>
<td>5.00–7.8</td>
</tr>
<tr>
<td>Volcanic (VOL)</td>
<td>5.00–6.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
enous across the three models. For example, NZL10 fixes a maximum magnitude of 8.20 for the fault sources in ASC compared to 7.6 used in the TWN15 and JPN14 models. The largest earthquakes generated by subduction interface sources included in the JPN14 and NZL10 models have a magnitude of 9.1 and 9.0, whereas in the TWN15 model the largest earthquakes modeled reach magnitude 8.0. Similarly, the maximum magnitudes for inslab earthquakes in the models are within a range comprised between 7.2 and 8.20. The NZL10 also contains the Taupo Volcanic Zone (hereafter, TVZ), defined as a volcanic region comprising extensional areas located in the North Island within the back-arc region; the maximum background source magnitude in this zone is 6.5. Fault sources in the TVZ are generally shorter than in the rest of the country with magnitudes of less than 7.0.

Analysis of Distributed Seismicity Sources in Active Shallow Crust

Distributed seismicity is the term adopted to describe earthquake sources that cannot be uniquely associated with a well-defined fault structure or earthquakes that can be associated with faults but, for modeling reasons, are assigned to diffused seismicity sources (e.g., in New Zealand; see Stirling et al., 2012, p. 1516). Distributed seismicity sources are generally represented in a PSHA input model either using area sources, that is, polygons within which the seismicity is supposed to occur homogeneously, or gridded seismicity sources often generated using a seismicity smoothing algorithm (e.g., Frankel, 1995). The MFD used to describe earthquake occurrence in the three models is a double-truncated GR distribution.

The JPN14 model contains a grid of about 15,000 equally spaced point sources used to model distributed seismicity in ASC (see Fig. 3); hypocenters are distributed between 3 and 35 km, and the range of magnitudes covered by this source typology is between 5 and 7.5.

NZL10 models distributed seismicity using a grid containing about 12,400 equally spaced point sources located at two hypocentral depths: 10 and 30 km. The maximum magnitude and the $b$-value of the GR relationship are computed using large zones, whereas the $a$-values are distributed over the grid. Both values are smoothed using a 50-km Gaussian seismicity-smoothing algorithm. The maximum value of magnitude for the earthquakes generated by distributed seismicity sources is 7.2, except in the Taupo Volcanic Zone ($M_{6.5}$). Rupture

Figure 3. Distributed seismicity sources in active shallow crust (ASC) tectonic environment. The probability of occurrence (per km$^2$ in 50 years) is for earthquakes larger than 5.0. Note that the (a) JPN14 and (b) NZL10 models use gridded seismicity sources, whereas the (c) TWN15 model uses area sources.

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finiteness is not considered in the calculation of hazard for this source typology. TWN15 contains 28 area sources that describe seismicity associated with earthquakes in the ASC between depths of 5 and 30 km. The minimum magnitude considered is 4.0, whereas the maximum is 7.0. Ruptures are modeled as rectangles for which area is computed using the Wells and Coppersmith (1994; hereafter, WC1994) magnitude-scaling relationship.

Overall, the three models reflect different modeling choices as well as some commonalities. For example, the thickness of the seismogenic layer is consistent across the three models but the choice of distributed seismicity source typology differs among them. In the case of the NZL10 model, the assumption of a point source even for magnitudes able to generate long ruptures is an aspect that will perhaps be considered in future updates of the models, given its role in the calculation of hazard (e.g., Monelli et al., 2014). Finally, ASC faults and distributed seismicity in the three models are combined without explicitly addressing possible double-counting problems, despite the magnitude range covered by faults and distributed seismicity being similar. This issue is largely attenuated by the assumption of a characteristic MFD for faults.

Analysis of Faults in Active Shallow Crust

The ESMs in the three PSHA input models contain onshore fault sources, which were defined using some of the most extensive and complete databases of active faults globally available. Figure 4 illustrates the surface projection of the fault surfaces and demonstrates the geographic completeness of the active fault databases for the three analyzed countries.

The MFD used in the three models to specify seismicity occurrence for shallow crust faults is a characteristic (or maximum magnitude) earthquake model. The JPN14 model contains 233 shallow faults with a time-independent model and 123 faults with a time-dependent behavior (see Fujiwara et al., 2009). The maximum magnitude assigned to a shallow fault

1A comprehensive description of the methodology adopted for the characterization of fault sources in the JPN14 model can be found in Fujiwara et al. (2009).
in ASC is 7.6, whereas the minimum magnitude assigned to a fault source is 6. The probability of occurrence for the nonparametric sources is computed assuming a Brownian passage-time model (Matthews et al., 2002). The TWN15 model includes 38 shallow faults in ASC modeled as simple-fault sources; the maximum magnitude assigned to a fault source in ASC is 7.6, whereas the minimum magnitude is 6.0. The MFD used is an incremental one, with a single magnitude bin resembling a characteristic earthquake model of occurrence. The number of shallow faults included in the NZL10 model is significant (530 faults in ASC and 196 faults in the VOL tectonic environment).

Figure 5a shows a comparison of the rate of scalar seismic moment released by each fault source versus its area (for JPN14, we consider only faults with a time-independent temporal occurrence model); scalar seismic moment rate is directly linked to the rate of seismogenic slip via the classical definition of scalar moment (e.g., Aki and Richards, 2002, p. 48). The overall trend in each dataset delineates a linear scaling between the logarithm of the area and the logarithm of scalar seismic moment rate. It is also evident that information from each model tends to form elongated clusters. The NZL10 dataset contains the faults with the largest surface area, as indicated by the histograms at Figure 5e.

The faults in the TWN15 are the ones releasing the highest rate of $M_0$ per unit of area, whereas the faults in the JPN14 model are the ones with the lowest density of moment rate released. This difference can be explained by the different levels of activity in the areas covered by the three models, although the range of variability seems high. The most interesting aspect of Figure 5 is the different scaling of moment rates with fault-surface area. In the NZL10 model, an increase of one logarithmic unit in terms of fault area corresponds to almost two units of moment rate (the slope of the dashed line is close to 2.0), whereas in the JPN14 model the increment of one (logarithmic) unit in area corresponds to only one unit in scalar seismic moment rate. Figure 5b, c, and d shows the values of area for each fault surface versus the corresponding scalar seismic moment computed from the value of the maximum magnitude.
assigned using the classical equation proposed by Hanks and Kanamori (1979). For reference, in each part of the figure we show the results obtained with the WC1994 magnitude-scaling relationship that aids in comparing the different datasets, even though it is used only in the TWN15 model for modeling finite ruptures. The JPN14 and TWN15 fault datasets are in good agreement with WC1994, whereas the NZL10 scales similarly but with consistently higher moment. In the NZL10 model, active shallow fault sources had been defined using magnitude-scaling relationships different than WC1994, although this difference, in our opinion, cannot completely explain the notable difference in scaling observed in Figure 5a.

Analysis of Subduction Interface Sources
Recent earthquakes like the 2011 Great East Japan earthquake ($M_w$ 9.0) emphasized the need for better accounting in national seismic-hazard models of rare but powerful earthquakes often generated by subduction interface sources. The three hazard models contain important subduction interface sources, such as the ones in the Nankai and Sagami areas in the JPN14 model, the Hikurangi and Fiordland subductions in New Zealand, or the Ryukyu arc in Taiwan.

The modeling of the earthquake process on subduction interface sources included in the JPN14 model is quite articulated and complex (see Fig. 6). The three source typologies adopted for the description of earthquake occurrence include point sources, finite ruptures for large magnitude earthquakes, and mega-subduction interface ruptures. Point sources are used to model earthquakes with magnitude comprised between 5.0 and 7.5, and finite ruptures cover the range between 6.8 and 8.30, whereas the mega-subduction ruptures cover a limited set of possible but extreme cases. Earthquake occurrence for point sources and finite ruptures is described using a double-truncated GR distribution. With respect to the modeling of mega-subduction interface ruptures, for some of them (e.g., the Nankai trough) the JPN14 model defines a number of possible mutually exclusive and collectively exhaustive sets of ruptures in a finite period of time and assigns to each of them a corresponding probability of occurrence.

The NZL10 model includes 11 subduction interface sources with a maximum magnitude of 9.0 in one case. The MFD used is a discrete truncated exponential distribution hav-
The TEM model contains three subduction interface sources for which seismicity is modeled using a characteristic earthquake model; the maximum magnitude assigned to subduction sources in the TWN15 model is 8.0, whereas the recurrence interval ranges from about 200 to 75 yrs. The temporal occurrence model is the usual Poisson model.

Analysis of Subduction Intraslab Sources

The JPN14 model describes earthquake occurrence within the slab using two typologies of sources—gridded seismicity and characteristic ruptures—and two separate regions—the northeast and southwest part—within which earthquake occurrence and ground-motion modeling are adjusted using region-specific parameters (see Fig. 7). Gridded seismicity sources with depths ranging from 13 to 180 km span the entire eastern coast of the three main islands (Honshu, Kyushu, and Hokkaido) as well as the small islands along the Izu-Bonin arc. Point sources are used to model the seismicity comprised between magnitudes 5.0 and 7.5 (in the northeast area) and 5.0 and 8.0 (in the southwest area) for which annual frequency of occurrence is described using a double-truncated GR distribution. Additional sources for magnitudes spanning 7.1–8.3 are modeled as finite ruptures (about 8000) uniformly distributed within the slab volume. In the NZL10 model, inslab seismicity is described using a grid of point sources. The hypocentral depth spans 10–90 km, and seismicity is specified using a double-truncated GR with $M_{\text{min}}$ 5.0 and $M_{\text{max}}$ 7.2. Intraslab subduction sources are defined in TWN15 as simple-fault sources for which seismicity occurrence is described via a double-truncated GR distribution covering the magnitude range between 5.0 and 7.8. The seismogenic layer is within 35 and 210 km depth.

The three models highlight quite different modeling approaches for inslab seismicity, particularly regarding the geometry of the sources. The JPN14 model is certainly the most complex one, because it includes a variety of source typologies differentiated on the basis of the magnitude range covered. The NZL10 and TWN15 show quite diverse approaches. The former adopts a seismicity-driven approach for assessing the position of future earthquakes, and the latter uses overlapped fault surfaces covering different depth ranges.

DISCUSSION

The three analyzed models provide insights on the current state-of-the-practice in PSHA modeling of complex active tec-
With respect to the modeling of hazard for ASC fault sources, there is a clear preference for the use of a characteristic earthquake MFD in the models reviewed but without any treatment of aleatory uncertainty (i.e., a fixed value of the area of rupture corresponds to a single value of magnitude instead of a distribution). This assumption is perhaps acceptable when the standard deviation is relatively small and the probabilities of exceedance considered for the hazard calculation is fairly large (e.g., 10% or 2% in 50 yrs). The interpretation and use of geologic information for the characterization of earthquake occurrence on ASC faults remains of key importance for the construction of ESMs. Although considerable progress has been made at the level of the single fault structure, particularly in the field of paleoseismology, further research is needed for a comprehensive characterization of fault systems (e.g., Field et al., 2014). The simple statistical analysis discussed in the section that is dedicated to faults in ASC emphasizes differences between the datasets included in the three national hazard models, especially in the way the rate of scalar seismic moment scales with respect to the area of fault sources. This is an important aspect to be considered especially when the characterization of fault structures in a hazard model is performed on the basis of regional deformation information (e.g., a regional convergence rate) or when comparing the geologically derived slip rates against the rates obtained from numerical modeling of the crustal deformation (see e.g., Petersen et al., 2013).

The description of the subduction earthquake process in the three models highlights very different modeling solutions for the interface as well as for the inslab seismicity component. With respect to the former, the NZL10 and TWN15 models account for the contributions of the largest ruptures on the subduction fault source, whereas ruptures of magnitude lower than the maximum on the subduction fault source are not included in TWN15 and NZL10 model. JPN14, on the contrary, contains interface sources spanning the full range of magnitudes (e.g., from about 5 and above). The largest ruptures generated by the most important subduction interface sources are described in terms of a finite set of mutually exclusive and collectively exhaustive sequences of events. To our knowledge, this is a unique example where mutual exclusivity is used to model a component of aleatory uncertainty in a PSHA model; its applicability to a larger set of cases, perhaps in similar tectonic contexts in other parts of the world, will have to be evaluated in the future. The variety of source types used in the JPN14 model and the variability of their characteristics make the analysis of contributions to various levels of hazard particularly interesting. As an example, for the city of Nagoya (Japan) Figure 8a shows the total hazard curve as well as the hazard curves computed for the various source components of the JPN14 model (this information is accessible on the J-SHIS website; see Data and Resources); Nagoya is located along the segment of the east coast of Honshu facing the Nankai trough. The plotted hazard curves demonstrate that the hazard is entirely controlled by the contributions provided by the Nankai interface source describing the occurrence of the largest events and that the contribution of sources of the other categories is pretty modest. For the Nankai interface, the JPN14 defines a probability of occurrence for a large event in the next 50 yrs close to one. On the contrary, in Sendai, which is located along
the Pacific coast in the northern part of Honshu, moderate-to-large interface and intraslab ruptures provide the most preponderant contribution to the overall hazard (see Fig. 8b). Sendai is situated in the area affected by the recent Great East Japan earthquake; in this area, the JPN14 model assigns a probability of occurrence in the next 50 yrs equal to 0 for an earthquake similar to the 2011 one.

With regard to the modeling of inslab seismicity, the JPN14 model is a common denominator between two more extreme modeling choices adopted in the NZL10 and TWN15 models. As an example, Figure 9a and 9b shows the hazard curves computed for Wellington and Taipei, respectively. Overall, the two plots show a similar trend, with contributions to the probability of exceedance coming from ASC and intraslab sources, although the control of ASC sources on the total hazard is stronger in the case of Wellington, due to the proximity of the Wellington fault.

CONCLUSIONS

New Zealand, Taiwan, and Japan are located on complex plate boundaries and are exposed to high levels of seismic hazard. In the recent past, these countries suffered extensive damage and a large number of casualties caused by earthquakes such as the 1999 Chi-Chi earthquake, the 2011 Christchurch earthquake, and the 2011 Great East Japan earthquake. Their scientific communities are actively engaged in the development of new hazard models aimed at supporting risk reduction policies.

The challenges facing Japan, New Zealand, and Taiwan are significant, due to the relatively limited duration of our observation period of earthquake phenomena. International cooperation is a process through which some of these difficulties are somewhat mitigated and the quality of national hazard models improved, particularly in cases where tectonic settings are so similar, like the ones discussed in this article, because numerous tectonic analogies are present.

The availability of hazard models in a common data format (in the current research we used the OpenQuake-engine format) facilitates comparisons and promotes a more transparent exchange of information.

An aspect that will require more extensive research in the future is a more widespread and formal treatment of epistemic uncertainty. Because this is a common shortcoming of all three models, the currently ongoing collaboration will certainly help in discussing common approaches for a more comprehensive treatment of epistemic uncertainty and, more generally, for a more consensual definition of ESMs at convergent boundaries.

DATA AND RESOURCES

The hazard input models utilized in this research, once released, will be available on the Global Earthquake Model (GEM) OpenQuake platform available at http://platform.openquake.org (last accessed September 2016). Information on the current collaboration between Japan, Taiwan, and New Zealand and on previous international collaboration promoted by National Research Institute for Earth Science and Disaster Resilience (NIED) is available at http://www.j-shis.bosai.go.jp/intl/tem/index.html (last accessed September 2016). The Japan Seismic Hazard Information Station (J-SHIS) can be accessed at http://www.j-shis.bosai.go.jp/ (last accessed June 2016). The website of the Taiwan Earthquake Model (TEM) initiative can be accessed at http://tec.earth.sinica.edu.tw/TEM/ (last accessed September 2016). The original New Zealand hazard model can be downloaded from the GNS Science website at http://
Specific information on the format used for the description of a probabilistic seismic-hazard analysis (PSHA) input model for the OpenQuake engine can be obtained from the GEM website (http://www.globalquakemodel.org) last accessed September 2016). The characterization of most of the active shallow crust (ASC) sources are found in the Active Fault Database of Japan (https://gbank.gsj.jp/activefault/index_e_gmap.html), last accessed July 2016) and in the Active Fault database maintained by GNS Science (http://data.gns.cri.nz/af), last accessed July 2016).

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