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SENSITIVITY STUDY OF SEISMIC HAZARD AND RISK FOR THE CONTINENT OF SOUTH AMERICA

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Abstract

In this paper, we present a sensitivity study of seismic hazard and risk for the Continent of South America by considering inputs from three hazard models: The 2016 United States Geological Survey (USGS) Sensitivity model for South America, the 2015 Global Earthquake Model (GEM) model for South America, and the 2015 Medina et al. model for Chile. The 2016 USGS Sensitivity model builds on the 2010 USGS model for South America that incorporated an earthquake catalog from 1900 through 2008, a fault database including about 100 crustal faults, a subduction-interface model based on observed seismicity rates, and ground motion models applied in the 2008 conterminous United States (U.S.) National Seismic Hazard Model (NSHM). In this paper, we develop the 2016 USGS Sensitivity model by updating the 2010 USGS model with a new earthquake catalog through 2013 and several new ground motion models. However, we apply the same fault parameters for subduction and crustal tectonics that were applied in the 2010 USGS model for South America so it is not an independent model and is only considered as a sensitivity study. The 2015 GEM model considers additional information for several countries on earthquake locations, faults, and ground shaking. The 2015 Medina et al. model for Chile incorporates new subduction-interface and crustal rupture models based on information obtained from experts in Chile. All three models incorporate subduction zone geometry that is based on non-planar representations of the three-dimensional geometry of subducting slabs as defined in the USGS Slab 1.0 model. Comparison of the three models is useful for understanding uncertainties in the modeling process. We find significant differences greater than 0.1 g and up to 50% in several places across South America, with respect to the 2010 USGS model, which suggests that additional seismic hazard research is necessary. To understand the impact of these types of hazard maps, we use the 2010 USGS South America hazard map (the 2016 sensitivity study model was not available for this analysis) to integrate that with population data and assess the number of people that are exposed to higher ground shaking levels.

Keywords: seismic hazard; seismic risk; earthquake shaking; South America seismic hazard

1. Introduction

Several seismic hazard models have been developed for South America over the past three decades that assess ground motion parameters (e.g., peak ground acceleration (PGA) and spectral acceleration) for varying hazard levels (e.g., 10% and 2% probability of exceedance in 50 years). The following description of seismic hazard work in this region is not a complete list of all hazard assessments but includes some of those studies known best to the authors. The Regional Center for Seismology for South America (CERESIS) developed one of the first hazard models for South America in 1996 by showing the intensities observed from historical earthquakes [1]. In 1999 the Global Seismic Hazard Assessment Project (GSHAP) published a global model for the western hemisphere [2]. The GSHAP seismic hazard efforts in South America included development of an earthquake catalog and a hazard assessment [2-4]. GSHAP models were developed for 10% probability of exceedance in 50 years and for peak ground acceleration. In 1988, CERESIS requested a United States Geological Survey (USGS) continent-based South American study of seismic hazard that included the influence of faults. The USGS developed hazard models that included fault and seismicity inputs for South America for PGA and spectral acceleration and these were published in 2010 [5] using the methodology of the USGS National Seismic Hazard Model (NSHM) [6, and references therein]. The 2010 USGS model was applied in early versions of the Global Earthquake Model (GEM) model for South America, but has been superseded by an alternative model, the South America Risk Assessment (SARA), that was released in late 2015 [7]. The new 2015 GEM model updates the previous GSHAP models. Other recent studies have been conducted for Ecuador [8] and Chile [9].

In this paper, we discuss differences in hazard models when applying the 2016 USGS Sensitivity model, the 2015 GEM model, and the 2015 Medina et al. [9] model for Chile. This analysis shows differences in hazard and points out information needed to improve hazard estimates in South America. It also shows the uncertainties associated with various modeling procedures. In addition, we examine the number of people exposed to various shaking levels for use in prioritizing risk across South America [10].

2. Models

The 2016 USGS Sensitivity model is an update of the 2010 USGS model [5] but incorporates a new earthquake catalog and ground motion models (GMMs). The new catalog is based on the 2015 GEM-ISC catalog [7] and shows high seismicity rates on the northern and western coasts of South America (Fig. 1). Many of the M 5 and M 7 earthquakes are located on the subduction interface. For this hazard sensitivity assessment, we develop zones to delineate the outer arc, subduction interface with depths down to 50 km, active crustal areas that encompass shallow crustal faults and deep seismicity, outer rise earthquakes, and craton events (Fig. 2).

In this hazard sensitivity analysis, we use the same methodology that was applied in constructing the 2014 U.S. National Seismic Hazard Model [6]. We assume that future large earthquakes will be located where earthquakes with $M \geq 5$ events have occurred in the past, and we calculate rates based on the long-term catalog that is smoothed spatially [6]. A truncated Gutenberg-Richter model (truncated at M 5 and at a maximum magnitude is used to extrapolate the rates to larger magnitudes. The earthquake rates are calculated on a grid with 0.1 by 0.1 degree cells. Finally, we calculate the hazard using GMMs that are applicable for shallow crustal, deep intraslab, subduction interface, and craton earthquakes. These new GMMs were implemented in the 2014 NSHM [6] and differ from the 2008 models by including more ground motion data and extensive modeling updates by the Pacific Engineering Research Center (NGA- Next Generation Attenuation) project [6]. Weights were assigned based on public workshops and outside review.

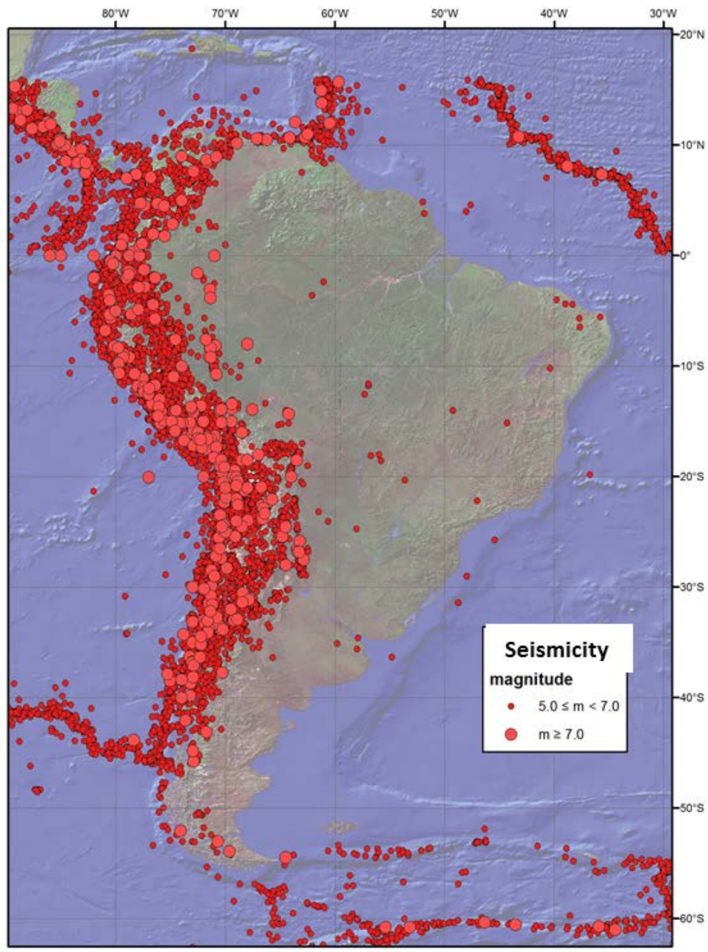


Fig 1. – Seismicity from 1964 to 2013 from the GEM SARA catalog for M ≥ 5 [7].

The 2016 USGS Sensitivity subduction zone model is based on historical seismicity, which is used to define the recurrence parameters of the magnitude-frequency distributions defined for the sources. Zones define the craton, active crustal, subduction, and outer rise regions. We apply the Slab 1.0 model geometry to account for the location of earthquake ruptures [11]. Fig. 2 shows the zones, based on geomorphic and historic ruptures, that we define for analyzing seismicity statistics. Zones 1 through 5 represent subduction areas associated with the upper 50 km of the subducting slab. All five zones have experienced earthquakes above M 8. Zones 2 and 4 have the highest rate of earthquakes. Zone 5 hosted the 1960 M 9.5 Chile earthquake. We allow for M 7 to M 9.5 in the two southern zones and M 7 to M 9 in the northern three zones based on historical earthquakes and global analogs. The 2016 USGS Sensitivity-gridded seismicity model accounts for shallow earthquakes that may be on unknown faults or other faults not considered in the hazard model. In addition, the model accounts for deep earthquakes (greater than 50 km) that are thought to be intraslab earthquakes associated with the subduction process. The model is smoothed using a 50-km Gaussian smoothing operator [6]. Shallow earthquakes are located in the active crustal region, the outer arc region, above the subduction zone, and within the craton (Fig. 2).

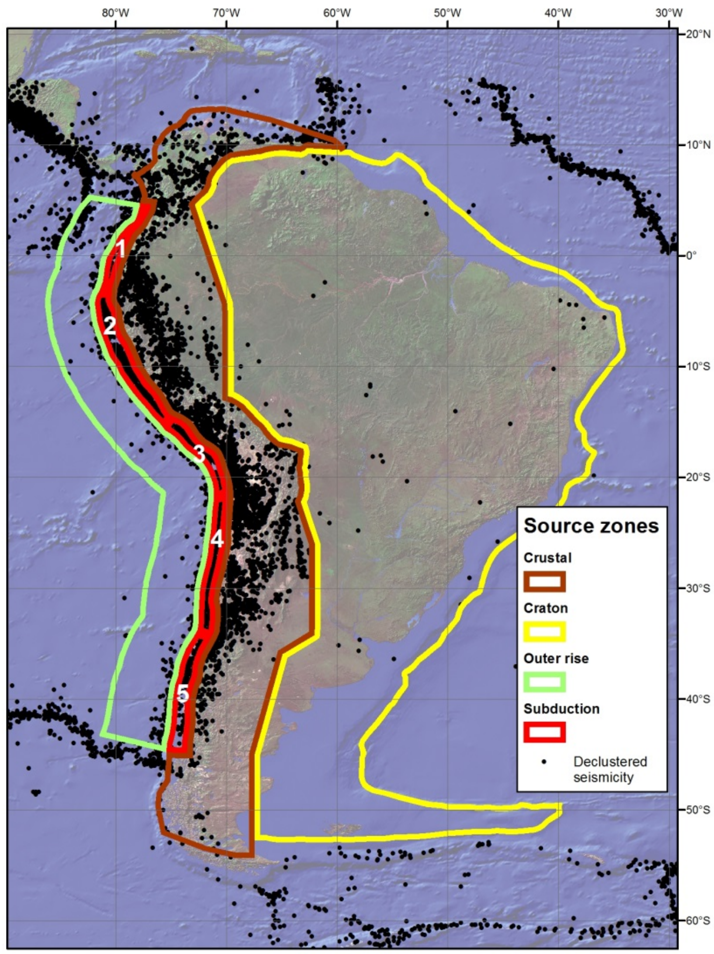


Fig. 2 – Source zones applied in the 2016 USGS Sensitivity model. Numbered subduction zones refer to subduction-interface faults (0-50 km) referenced in the 2010 USGS model [5].

Reviews of various fault compilations from individual countries provide sufficient constraints to include 100 Quaternary faults recognized in South America. We applied the fault model from the 2010 USGS model for South America in the 2016 USGS Sensitivity Model presented here (Fig. 3). Significantly less than one half of the known Quaternary faults have sufficient data to characterize geometry and activity rates across South America. With the exception of historical ruptures in South America, details of significant earthquakes and slip rates on Quaternary faults are poorly constrained. Many faults are under-studied, and compilers did not assign a slip rate to nearly 80 percent of the faults. Over half of the remaining faults were not included in this model because they are very short and the calculated maximum magnitude is less than M 6.5. The 250 faults not included in the model generally are the oldest (defined as Quaternary in the compilations) and slowest (≤0.2 mm/yr) faults, which contribute little to hazard. Additional detailed investigations of the many potential sources in South America will improve future seismic hazard estimates.

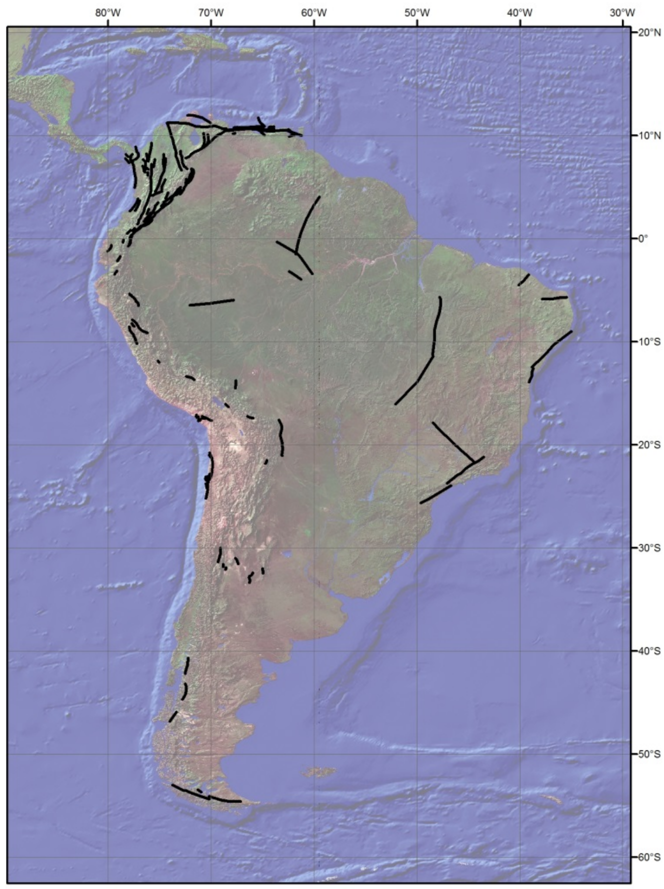


Fig. 3 – Faults considered in the 2010 USGS model and 2016 USGS Sensitivity model.

For the 2016 USGS Sensitivity model, we apply GMMs for subduction-interface and intraslab earthquakes, crustal earthquakes on faults in active tectonic regions, as well as crustal earthquakes on faults in cratonic regions. These are the same GMMs as those applied in corresponding tectonic regions in the 2014 U.S. NSHM [6]. For subduction-interface earthquakes, we have compared models with data at distances from 100 to 1000 km and found that the two older GMMs over-predict the motions compared to global broadband data. Fig. 4 shows subduction-interface GMMs applied in the 2010 USGS model (ABglobal and Youngs older models) and GMMs applied in the 2016 USGS Sensitivity model (AM09, BCHydro, and Zhao newer models). The ABglobal and Youngs older models were not considered in the 2016 USGS Sensitivity model because they have different spectral shapes compared to recent strong shaking data. For example, the newer models (AM09, BCHydro, and Zhao models) are higher in the near field and fall of faster with distance compared to the older models (ABglobal and Youngs). Long period ground shaking levels also differ between the new and older models. Additional research will help us better understand these ground shaking issues.

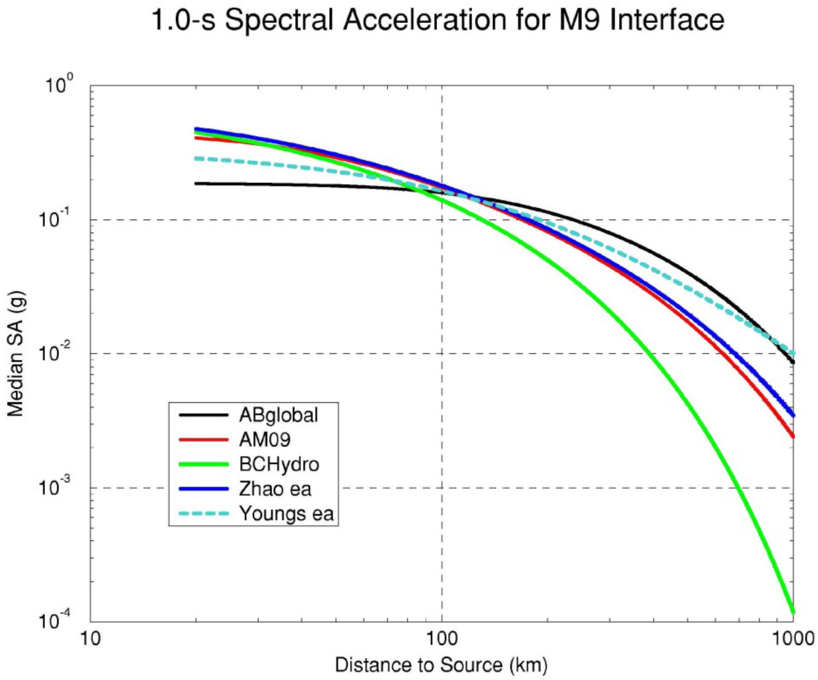


Fig. 4 – Spectral accelerations for M 9 subduction-interface earthquakes. The older (ABglobal and Youngs) models were not applied in the 2016 USGS Sensitivity model. Note that the newer models (AM09, BCHydro, and Zhao) fall off faster than the older models considered in the 2010 USGS model [5].

The 2015 GEM model [7] incorporates a new instrumental seismicity catalog for South America from 1930 to 2013 that is based on several national and international catalogs. This catalog is used to compare with the 2010 USGS model catalog (Fig. 5). In addition, a database of active faults was compiled with information from national agencies and universities in Colombia, Venezuela, Ecuador, Bolivia, Brazil, Argentina, Peru, and Chile. This database is not yet available, but will be compared with the 2010 USGS model when it is. The 2015 GEM model [7] also incorporates a strong-motion database with recordings from about 370 earthquakes. This information will be very valuable in updating the hazard models when it becomes available.

Medina et al. (2015) [9] prepared seismic hazard maps for Chile using the same methodology and framework as in the 2014 U.S. NSHM [6]. We refer to this model as the 2015 Medina et al. model for Chile. Medina et al. (2015) [9] updated fault-specific hazard in Chile and neighboring countries. One important change compared to the 2010 USGS model [5] for South America was to increase the modeled slip rate on the Magallanes (or Lago Fagnano) fault to about 7 mm/year. This results in significant hazard at the 2% in 50 year probability level for sites near this plate-boundary fault. Another important change was to consider subduction throughout Chile as a Gutenberg-Richter process, without a characteristic-event epistemic model branch. The a- and b-values were determined purely from catalog seismicity. The Gutenberg-Richter magnitude frequency distribution was truncated at maximum magnitude of M 9.75, and applies a taper from M 9.5 onwards. The inferred seismic convergence rate was compared with geodetic models that indicate about 6.5 cm/year of Nazca – South America plate convergence. Medina et al. (2015) [9] considered a subduction source branch that breaks the Antarctic plate as well as the Nazca plate, although this uncertainty branch was only given 20% weight. The 2016 USGS Sensitivity model does not currently consider Antarctic plate rupture, at least with large-magnitude events. Although historical large-magnitude, plate-subduction events are absent from seismicity catalogs, geologic evidence suggests that such events should be considered. The 2016 USGS Sensitivity subduction model includes a characteristic rupture branch with M = 9.5 in Chile, with southern rupture termination just north of the Chile rise, as was observed in the 1960 M 9.5 megathrust event. A third difference between the 2015 Medina et al. model for Chile [9] and the 2014 U.S. NSHM [6] was to use a reference rock V_{s30} of 900 m/s, rather than the USGS preferred value of 760 m/s.

3. Comparisons of Hazard Model Components

In all the hazard comparisons below, we calculate the hazard for 1-Hz spectral acceleration with a 2% probability of exceedance in 50 years for a firm rock site condition (V_{s30} of 760 m/s). We study the sensitivity of hazard to the 2016 USGS Sensitivity shallow (0-50 km) seismicity model, deeper (50-150 km) seismicity model, subduction-interface model, and the shallow crustal fault model.

The 2016 USGS Sensitivity seismicity model describes hazard from historical earthquakes in three depth ranges: 0-50 km, 50-100 km, and 100-150 km. Figure 5 shows the hazard calculated for the shallow seismicity in the 2010 USGS model [5] and the 2016 USGS Sensitivity model that incorporates the new 2015 GEM catalog [7]. We incorporate different GMMs appropriate for each specific type of earthquake similar to the way they were applied in the 2014 U.S. NSHM [6]. The 2016 USGS Sensitivity model and 2010 USGS model [5] maps are quite similar in overall appearance, but there are some significant differences. For example, the hazard near Buenos Aires, Argentina, is significantly reduced in the 2016 USGS Sensitivity model. Other places across the continent are higher in one model and lower in the other. For example, near Bogota the hazard is about 0.27 g in the new model and was up to 0.5 g in the previous model. This result indicates the importance of the earthquake catalog in the hazard calculation and points out the need for additional research.

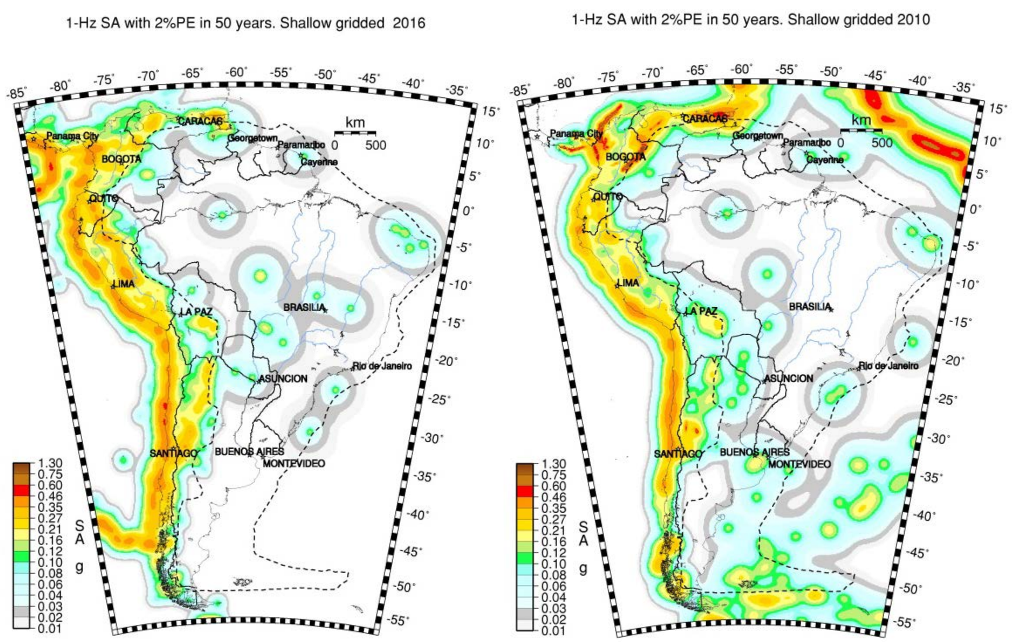


Fig. 5– Shallow-gridded seismicity hazard for 2016 USGS Sensitivity model with 2015 GEM catalog [7], left, and 2010 USGS model [5], right. The high hazard in the northeastern portion of the map is from a fault in the 2010 USGS model that is not included in the 2016 USGS Sensitivity model.

A comparison of the 2016 USGS Sensitivity model and the 2010 USGS model [5] for deep-gridded seismicity (depths from 50 km to 150 km) is shown in Fig. 6. As in the shallow crustal seismicity model the deep seismicity models also result in significant hazard differences. In the 2016 USGS Sensitivity model, we apply the 2015 GEM catalog [7] and the new GMMs considered in the 2014 U.S. NSHM [6]. We set the depth at 65 km for the earthquakes between 50 and 100 km and 115 km for depths between 100 and 150 km. The hazard is high from these deep earthquakes and reaches about 0.4 g for 1-Hz spectral acceleration. The contribution is significant for both 50 to 100 and 100 to 150 depths. The 2016 USGS Sensitivity model hazard is up to 50% lower near the coast but increases in several regions up to 50% from the introduction of the new 2015 GEM catalog [7] and 2014 U.S. NSHM GMMs [6].

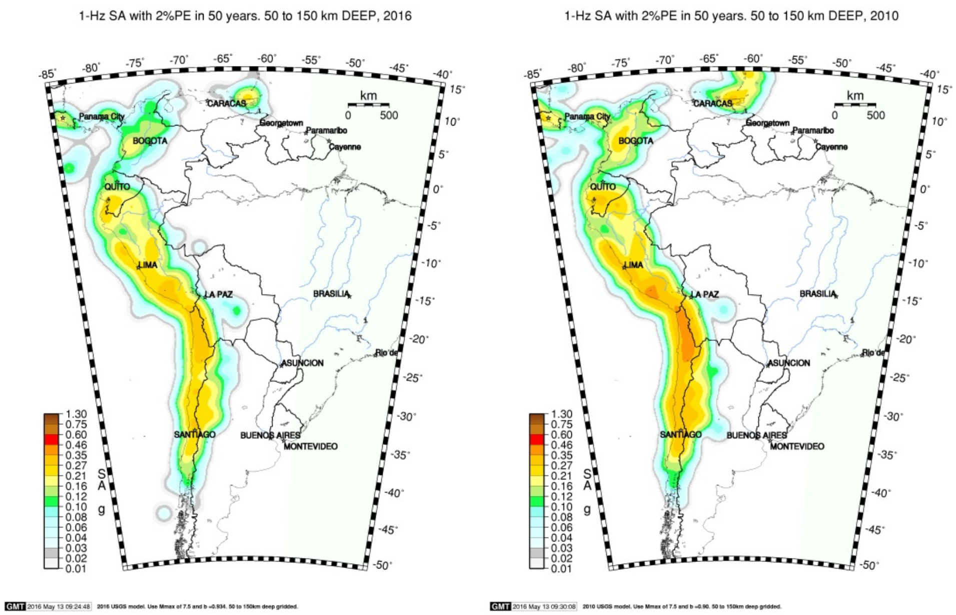


Fig. 6– Deep-gridded seismicity for the 2016 USGS Sensitivity model using the 2015 GEM catalog [7] left and 2010 USGS model [5] right.

A hazard comparison of the older GMMs from the 2010 USGS model [5] and the newer GMMs from the 2016 USGS Sensitivity model is shown in Fig. 7. Hazard is generally higher along the coast and lower inland when applying the 2016 USGS Sensitivity model, due to the new subduction zone GMMs. Hazard in the 2016 USGS Sensitivity model is typically up to 50% higher along the coast and up to 50% lower inland. This variability is entirely due to the introduction of new GMMs that also are higher near the shallowest portion of the subduction zone but decay faster with distance [6]. The 2016 USGS Sensitivity model changes related to deep earthquakes are opposite those of subduction-interface earthquakes along the coast.

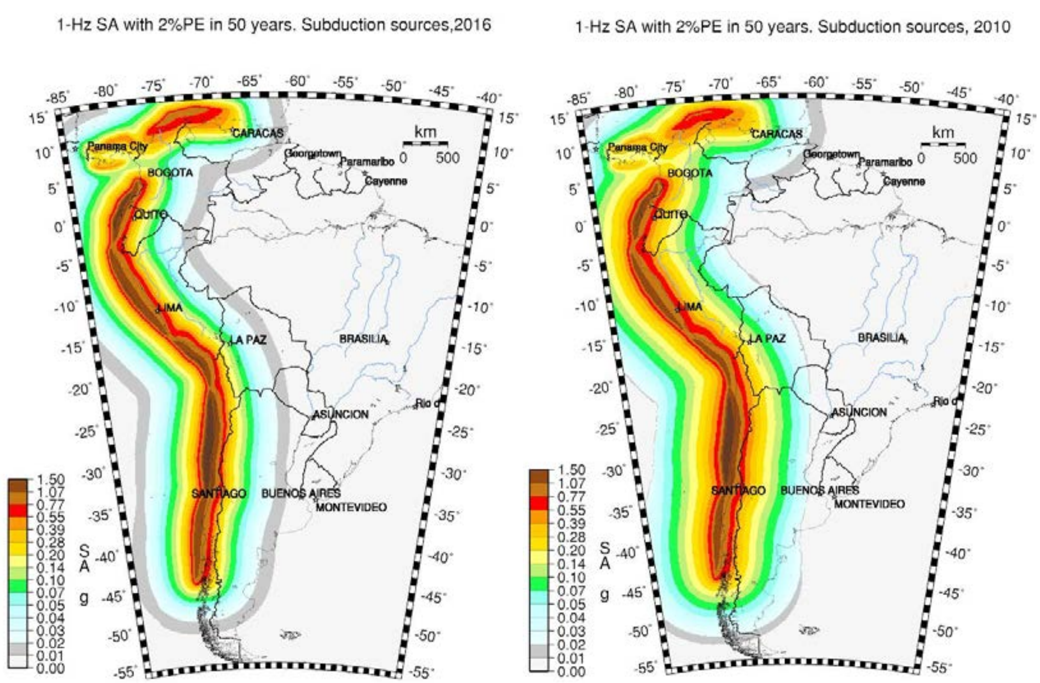


Fig. 7 – Subduction-interface hazard for the 2016 USGS Sensitivity model (which includes 2014 U.S. NSHM GMMs [6]), left, and the 2010 USGS model with older equations, right.

The 2015 Medina et al. model for Chile [9] includes alternative subduction-interface and crustal fault models, as shown in Fig. 8. The 2015 Medina et al. model for Chile [9] shows higher hazard in the Patagonia region due to a changed consensus from local geologists and seismologists on the slip rate of the Magallanes (or Lago Fagnano fault) that increases from 1 mm/yr to 7 mm/yr. The hazard from this fault in the 2010 USGS model [5] for the 2% probability of exceedance in 50 years maps is significantly lower.

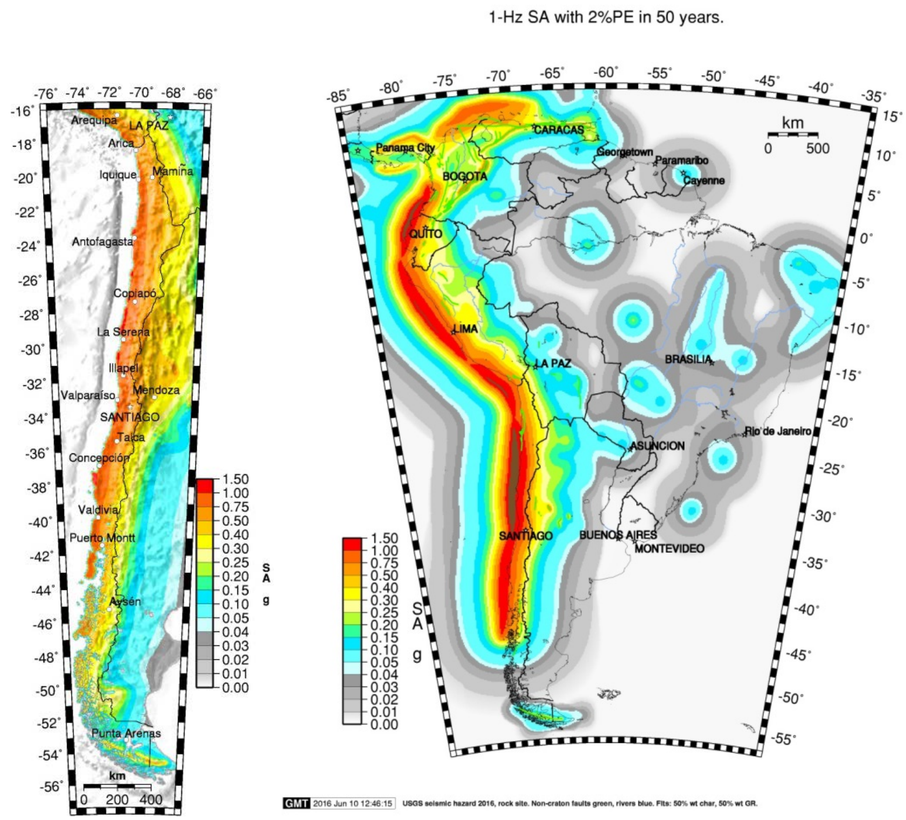
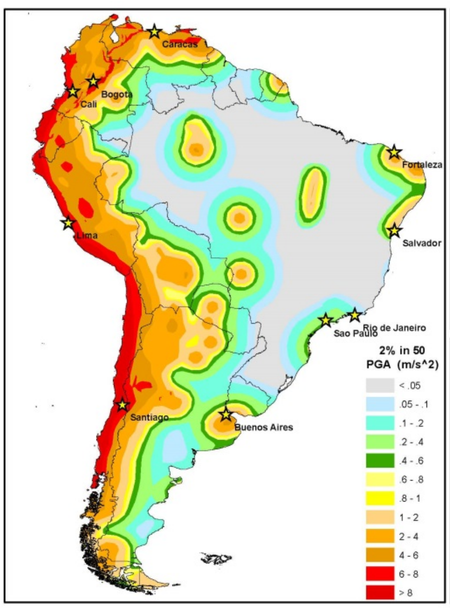


Fig. 8 – Seismic hazard in Chile from subduction-zone interface and shallow faults from the 2015 Medina et al. model for Chile [9], left, from the 2016 USGS Sensitivity model, right.

4. Results

Seismic hazard across South America from the 2010 USGS model is shown in Fig. 9. The 2016 Sensitivity Study model was not available when this analysis was performed so we applied the 2010 USGS model. The hazard is high along the western and northern coasts and reaches ground motions of about 0.8 g (PGA) at a 2% probability of exceedance in 50 years. This figure shows that a large part of the population of South America is exposed to high seismic hazard [10]. About 30% of the population lives in the areas where we could expect to see damage from future earthquake ground shaking (above 0.4 g). About 175 million people live in regions where we might expect to see some level of damage (minor non-structural or greater) at the building code levels shown here (0.16 and greater PGA levels, which corresponds to Modified Mercalli Intensity levels greater than VI). Future efforts should better define the hazard models. For example, using the new 2015 GEM catalog [7], the hazard near Buenos Aires, Argentina is lower than shown in the 2010 USGS model [5].



Hazard	# of People	Population%
0 - 0.2	129,677,119	32.5%
0.2 - 0.4	45,351,509	11.4%
0.4 - 0.8	28,719,648	7.2%
0.8 - 1.6	17,773,908	4.5%
1.6 - 3.2	34,206,812	8.6%
3.2 - 4.0	19,834,762	5.0%
4.0 +	122,690,458	30.8%

Largest South American Cities

Place	Hazard	Population
Buenos Aires	2.21 m/s^2	13,076,300
Sao Paulo	0.34m/s^2	11,244,369
Lima	9.22 m/s^2	8,481,415
Bogota	4.44 m/s^2	7,674,366
Santiago	9.30 m/s^2	6,685,685
Rio de Janeiro	0.13 m/s^2	6,323,037
Caracas	4.87 m/s^2	3,000,000
Salvador	1.30 m/s^2	2,711,840
Fortaleza	2.02 m/s^2	2,400,000
Cali	5.54 m/s^2	2,392,877

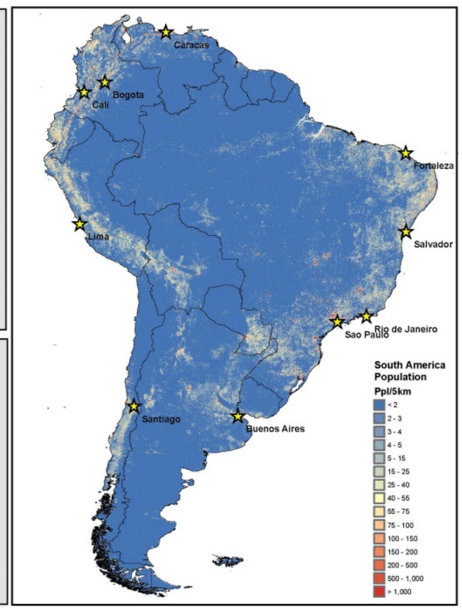


Fig. 9 – 2010 USGS model hazard (2016 USGS Sensitivity model not available when analysis was made) [5], left, and the exposure for South America from Jaiswal and others [10], right.

5. Conclusions

The hazard along the western and northern coasts of South America is high. This is mostly due to the high rates of seismicity in the subduction interface and intraslab components of the 2016 USGS Sensitivity-hazard model. Shallow crustal faults near several major metropolitan areas are also important sources of hazard. Refining the input catalogs, fault databases, ground motion models, and methods would aid the hazard assessment. A collaborative national and international effort would help in better defining and assessing risk to the millions of people who live in these hazardous areas. Results presented in this sensitivity study will enable us to develop an updated model for South America.

6. Acknowledgements

Many scientists provided information used in producing this model. We appreciate the support of CERESIS scientists in providing input and advice in modeling.

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