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PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR SOUTH PACIFIC ISLANDS

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ABSTRACT

A probabilistic seismic hazard model was developed for seven countries in the South Pacific, including Fiji, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. A regional seismicity model was built based on historical and instrumental earthquake catalog, subduction zone segmentation and plate motion information, and available data on crustal faults. Several historical earthquake catalogs were combined to create a comprehensive database spanning from 1900 to 2008. A variety of magnitude scales were converted to moment magnitude using regression relationships. We delineated 46 seismic source zones to capture the seismic activity on subduction zones, fore-arc and back-arc regions, transforming zones, and background areas. The concept of regional smooth seismicity was used to create a gridded-seismicity model for non-characteristic shallow and deep earthquakes. For characteristic earthquakes for faults and subduction zones, their magnitudes and recurrence times were formulated based on historical and instrumental seismicity, regional tectonics, geodetic studies, and plate motions. To account for the hazard from multi-segment ruptures, a stochastic cascading model was formulated and applied to the subduction segments that have cascading rupture histories or may potentially produce cascading ruptures. To calculate the ground motion, we used different sets of attenuation equations to account for the different types of earthquakes, such as subduction interface, intra-slab, deep, and crustal events. Site conditions near four capital cities, as characterized by seismic microzonation, were considered to account for site amplification. We compared the seismic hazard from this study with that of other published research, to evaluate the effects of our integrated seismicity, three-dimensional source geometry, and local site conditions models on regional seismic hazard analysis.

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Introduction

The South Pacific Island Countries (SOPAC), located on one of the most active subduction zones in the world, are exposed to a very high seismic risk. A uniform seismic hazard study for the entire region has been carried out by the Global Seismic Hazard Assessment Program (GSHAP); however, this study does not have sufficient spatial resolution to be reliably used at a local level. The GSHAP project was designed to create a global seismic hazard map for the entire world. Although the seismic hazard of countries such as Fiji, Papua New Guinea, and Vanuatu has been studied in detail (Jones 1998; Suckale and Grünthal 2009), the methodologies used were different and the seismic hazard was not expressed in a uniform way because the research was completed by different authors and at different times. Furthermore, detailed seismic hazard studies for countries such Tonga, Tuvalu, Samoa and the Solomon Islands are sparse. As part of a project for the World Bank, we constructed a regional seismicity model for the SOPAC region. The main objective of this study is to create a uniform regional seismic hazard model that has sufficient detail to capture the spatial variation in the hazard and that can be used to realistically assess the seismic risk across the region.

Tectonic Settings

The tectonic setting of the SOPAC region is very complicated. The earthquakes, volcanoes, ground deformation and tsunamis that can cause destruction in the region all result from the interaction of four major plates (Figure 1): The Pacific (PA), Australia (AU), Philippine Sea (PS) and Sunda (SU) plates.

North of the Bird Head, the Philippine Sea plate subducts to the west under the Sunda plate at a rate of about 100 mm/year. South of the Bird Head, the Australia plate subducts beneath the Sunda plate at a rate of about 70-80 mm/year. The convergence between the AU and PA plates results in a shortening at the plate boundaries along Papua New Guinea, the Solomon Islands, Vanuatu and Fiji of about 100 mm/year. At the New Hebrides subduction zone, large variations of convergence relative to the Australia plate is observed using GPS data. The Kermadec and Tonga trenches absorb the collision between Pacific and Australia plates. The convergence rate between the two plates is about 60-70 mm/year at the Tonga segment and approximately 50-60 mm/year at Kermadec segment. Intraplate earthquakes are the dominant hazard in Fiji, as the two main islands are located in the south end of the active transform fault.

Due to the fast convergence rate of the plates and the seismotectonic complexity of the region, the SOPAC is very seismically active. Large subduction interface, deep, and intraplate earthquakes may generate high levels of ground motion and tsunamis, which leads to a great seismic and tsunami hazard in the island countries. The July 17, 1998 PNG tsunami disaster induced by a magnitude 7.1 earthquake killed at least three thousand people. The most recent large subduction earthquake along Solomon Islands was a magnitude 8.1 earthquake on April 1, 2007. The most damaging earthquake to occur in Fiji in the last 100 years was a magnitude 6.7 intraplate event that occurred on September 14, 1953. Two large earthquakes of magnitudes 7.6 and 7.8 occurred along the NH subduction zone on October 7, 2009. A magnitude 8.0 earthquake struck the northern end of the Tonga trench on September 29, 2009. The earthquake and its resulting tsunami were responsible for 161 deaths in Samoa, American Samoa, and Tonga.

Data

Historical Earthquake Catalogs

Historical earthquake data for the Pacific islands is considered to be incomplete, and the existing catalogs are relatively short. Three historical earthquake catalogs were merged to obtain a relatively complete catalog for the entire region. The three catalogs are:

1. Preliminary Determined Earthquake (PDE) catalog by USGS National Earthquake Information Center, 1973 - 2008.
2. Engdahl et al. (1998) relocated global earthquake catalog, 1964 - 2002.
3. USGS/NOAA significant earthquakes, 1900 - 1963.

Before merging the catalogs, the magnitudes reported in the PDE and Engdahl (1998) catalogs were converted to moment magnitude (M_w) using the magnitude regression relationships established by Suckale and Grünthal (2009).

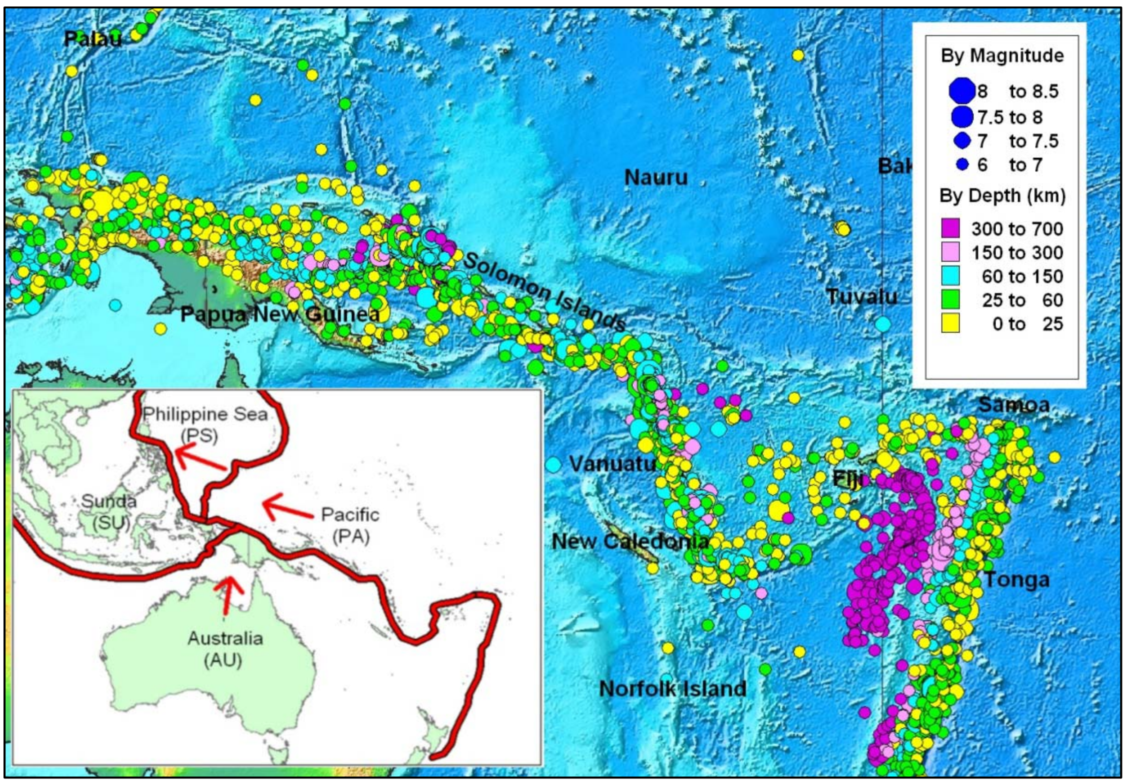


Figure 1. Regional Tectonic Setting and seismicity in the SOPAC region. Red arrows in the inserted map show the plate motions relative to Sunda (SU) plate. Colored dots in the main map are historical earthquakes (M≥6.0) from 1900 to 2008. Colors represent epicenter depth ranges and circle size shows the magnitude ranges.

The USGS/NOAA catalog is very comprehensive, but contains a large amount of uncertainty regarding the location, depth, and magnitude of earthquakes. Thus only large earthquakes (M≥6.5) in this catalog were used to construct the seismicity model. Nishenko (1991) also reported some large historical subduction earthquakes and their surface magnitudes. Large discrepancies were found between the magnitudes reported in the two catalogs. We therefore derived a regression relationship between the USGA/NOAA magnitudes and M_s using large magnitude events. After converting the USGS/NOAA magnitudes into M_s, the equation by Suckale and Grünthal (2009) was applied to obtain M_w.

The three catalogs were then merged. We declustered the merged catalog using the methodology of Resenberg (1985). Figure 1 shows the large historical earthquakes included in the final combined catalog. Completeness time in the catalog varies slightly for different source zones (please refer to the next section for source zones). Generally, the catalog is considered to be complete for events of magnitude 5.5 or greater that have occurred since 1964. The completeness times of large earthquakes varies by region. Along the Tonga subduction zone, events of magnitude 7.5 and greater are complete since 1900. For Fiji and its vicinity, events of magnitude 6.5 and greater are complete since 1910. For other regions, events of magnitude 7.0 and greater are complete since 1900.

Subduction segments and crustal faults

Among the seven South Pacific countries studied in this project, Papua New Guinea, Solomon Islands, Vanuatu, and Tonga are located in subduction zones. Segmentation of the subduction zone is a constraint on the location and size of mega-thrust earthquakes. In this study, we segmented the subduction zones according to previous studies (Nishenko 1991) with adjustments based on the most recent historical earthquake ruptures.

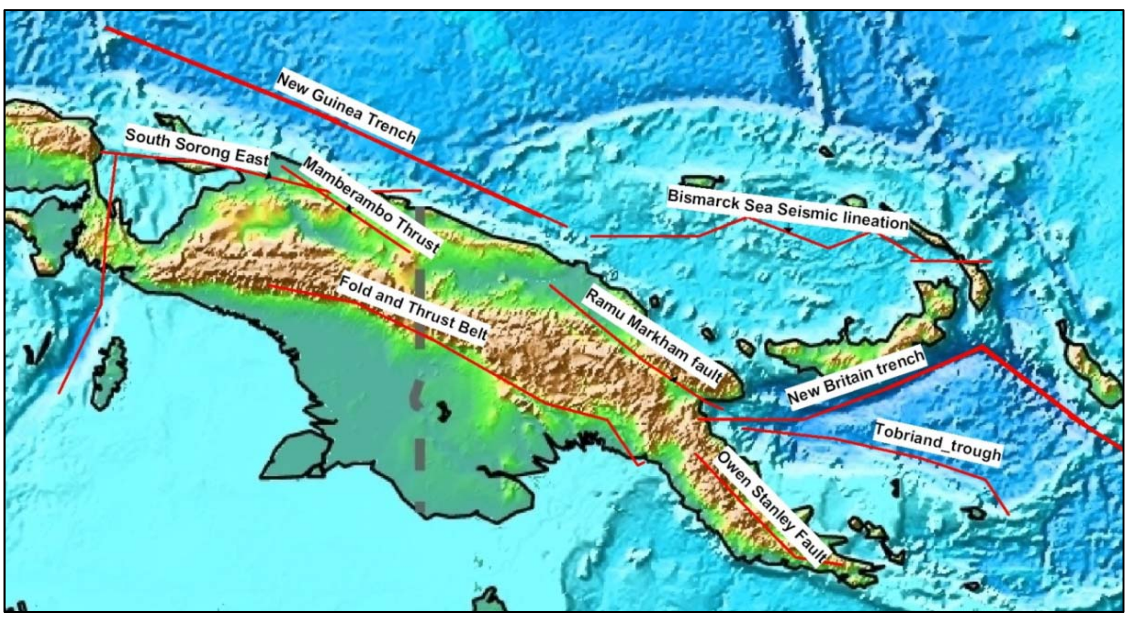


Figure 2. Crustal faults and subduction trenches in and around Papua New Guinea.

In addition to the subduction of plates, crustal faults are also a hazard. The 1953 Suva earthquake, the most damaging earthquake to occur in Fiji, took place on a near shore crustal fault. Potentially active faults have been identified in Viti Leu of the Fiji Islands. Rahiman (2006) summarized the fault parameters and deduced the maximum credible earthquakes that could occur on these crustal faults (Table 9.3 and Figure 9.8 in Rahiman 2006).

Some of the crustal faults and subduction trenches in and around Papua New Guinea are illustrated in Figure 2. Puntodewo et al. (1994) suggests that, based on GPS measurements, the compressional deformation rate across the PNG highlands and the Mamberambo thrust belts is less than 15 mm/yr. The plate model by Tregoning et al. (1998) suggests that a left-lateral slip of approximately ten mm/yr in the Owen Stanley Range. Ramu Markham fault serves as a boundary between South Bismarck and Australia plates. The convergence rate on this fault is about 29 mm/yr at 145.5°E, and 50 mm/yr at 147°E (Tregoning et al. 1998).

Modeling the Regional Seismicity

We delineated 46 source zones in order to model the regional seismicity based on regional seismotectonics and historical seismicity (Figure 3). The source zones capture subduction zones, fore arc and back arc regions, transforming zones, and background area. The delineation of subduction zones is based on Nishenko (1991) subduction segmentations with some adjustments, such as combining neighboring zones according to the recent historical earthquake ruptures. For the regions around Vanuatu, the source zones are based on Suckale and Grünthal (2009), while for the region around Fiji, the zones are based on Jones (1998). The seismicity in each source zone is modeled at two depth layers: a shallow layer featured by subduction interface and shallow crustal events, and a deep layer featured by subduction intraplate and deep earthquakes

Seismicity in the SOPAC region can be attributed to crustal earthquakes on known faults, large subduction interface earthquakes, large subduction earthquakes, such as normal faulting intraplate and outer rise events, and shallow background and deep seismicity. We determined the characteristic earthquake magnitudes and the mean recurrence times of the subduction segments using historical rupture information and plate tectonic data. For those subduction segments with possible cascading ruptures, various cascading scenarios were considered using a stochastic modeling scheme. We modeled seismicity on the known faults by estimating the recurrence rates of characteristic earthquakes from slip rate and historical earthquake data. Magnitude uncertainties were considered for characteristic earthquakes on faults and in subduction zones. We modeled the shallow background and deep seismicity with a gridded seismicity approach. Gutenberg-Richter a- and b-values were determined using historical earthquake data, and the upper bound magnitudes were determined from regional tectonics and the largest magnitudes in the historical catalogs. For the subduction zones, a three-dimensional model was applied to model the spatial distribution of subduction related interface and intraplate earthquakes.

The largest recorded historical earthquake in the studied region had a magnitude of less than 8.5. Because the historical catalog is short, we cannot rule out the possibility that a magnitude 8.5-9.0 mega-thrust event could occur in this region, especially in the trench from New Britain to the Solomon Islands where the subduction plate is young and fast moving. A moment conservation principal was used to estimate the recurrence of such mega earthquakes. The geologic moment rates ($\dot{M}_g$) were calculated based on plate convergence rates, subduction length and width, and an estimated coupling coefficient. Next, the total seismic moment rate ($\dot{M}_s$) for the region was calculated by fitting the historical earthquake data into a truncated Gutenberg-Richter curve. We assumed that the moment rate difference of $\dot{M}_g$-$\dot{M}_s$ will be consumed by mega earthquakes of magnitudes 8.5-9.0. The estimated recurrences of such earthquakes are ~600 years, ~600 years, ~1400 years, and ~2700 years for New Britain and the Solomon Islands, Vanuatu, Tonga, and Kermadec subduction zones, respectively.

Figure 4(a) illustrates the historical and modeled seismicity rates for the study region. It is clear that our modeled seismicity rates are very consistent with historical earthquake rates. Figure 4(b) shows the same for an exemplary smaller region: zones 11 and 13 around Solomon Islands.

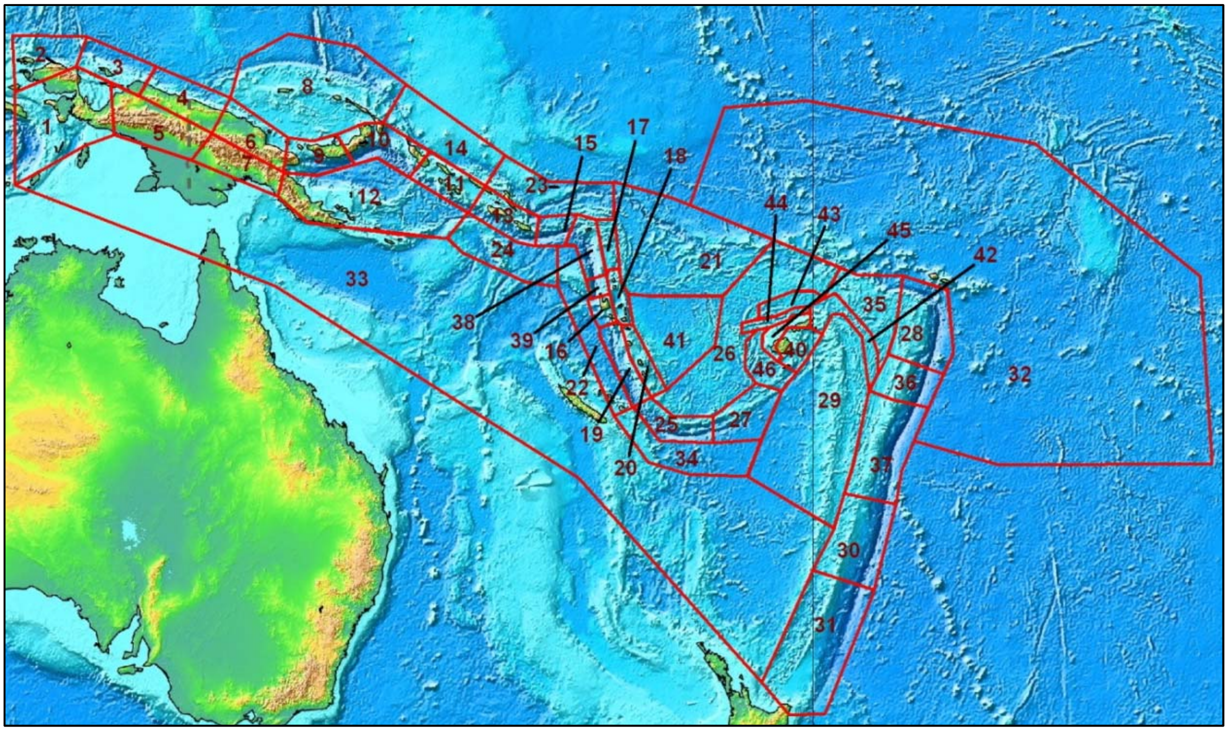
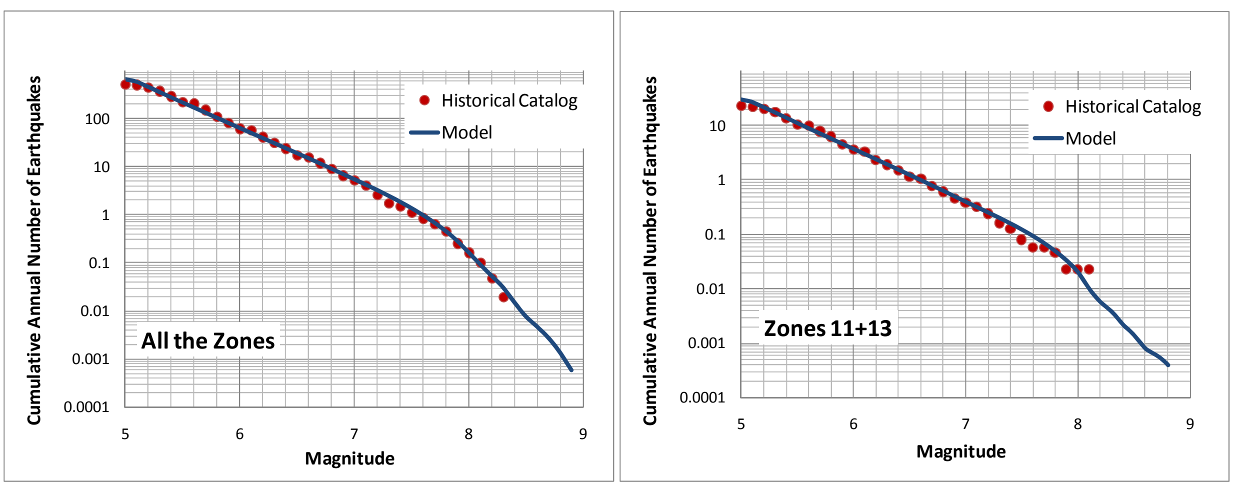


Figure 3. Seismic source zones used in constructing the seismicity model. The zones are delineated according to seismotectonics and the distribution of historical seismicity.



(a) (b)

Figure 4. Cumulative magnitude-frequency distributions from the model (blue curve) and historical catalog (red dots). (a) magnitude-frequency distributions for the whole study region; and (b) magnitude-frequency distributions for source zones 11 and 13, where the Solomon Islands are located.

Ground Shaking Hazard

Seven attenuation relations were used to calculate ground motion. For crustal earthquakes, four Next Generation Attenuation (NGA) relation models of equal weight were used: Boore and Aktinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2009), and Abrahamson and Silva (2008). We adopted Youngs et al. (1997), Atkinson and Boore (2003), the global model, and Zhao et al. (2006) to estimate ground motion for subduction and deep earthquakes. Half weight was given to Zhao et al. (2006), and the other half weight was split equally between Youngs et al. (1997) and Atkinson and Boore (2003).

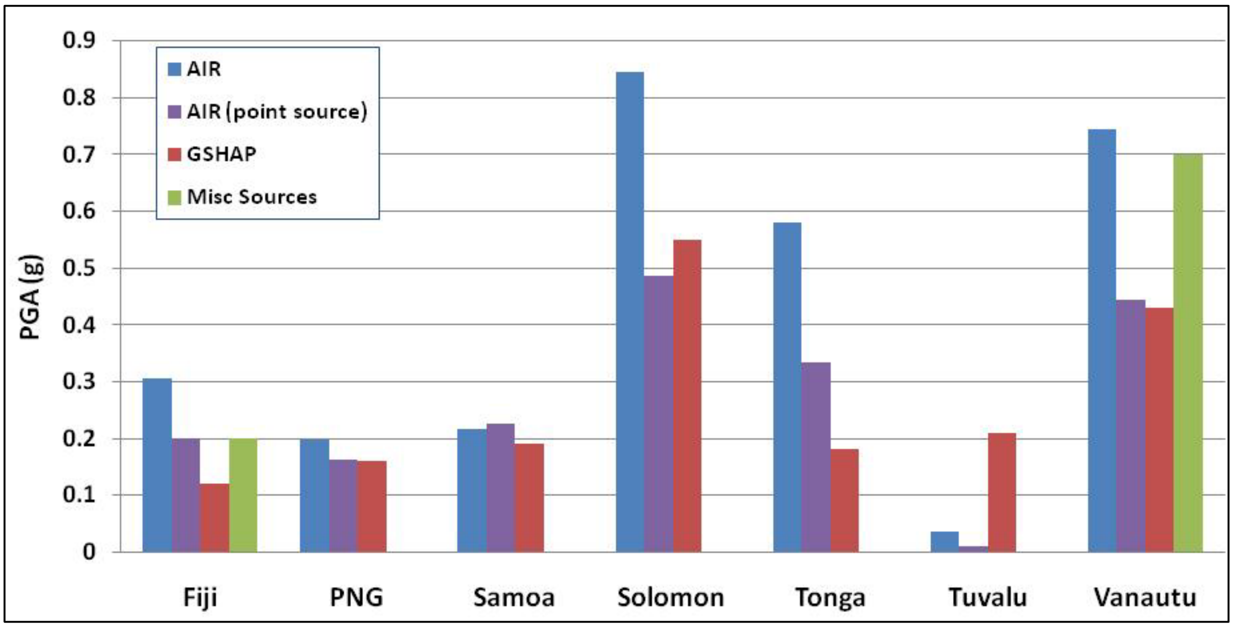
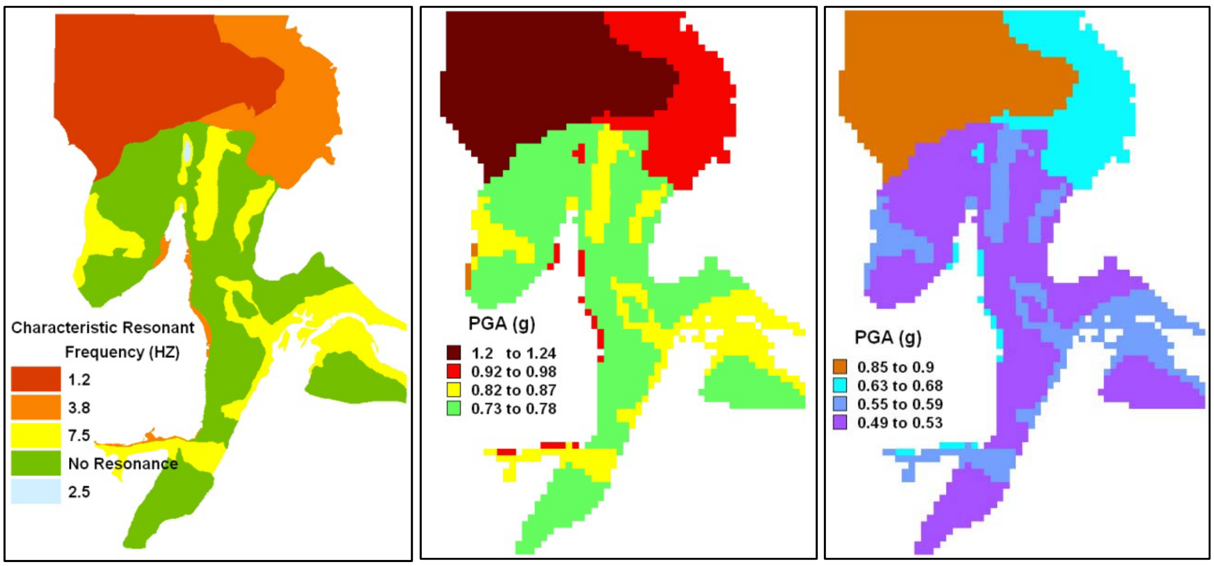


Figure 5. Expected PGA (g), with a 10% probability of occurrence or exceedance in 50 years (475 year mean return period), for rock sites at the capitals of seven SOPAC countries. The blue bars are PGA values from this study that use fault rupture instead of point source in the distance calculations for events. The purple bars are PGA values from this study that use point source in distance calculations for events. The red bars are PGA values by GSHAP. The green bars are the results of other studies (Jones 1998; Suckale and Grünthal 2009).

Figure 5 illustrates the expected peak ground acceleration (PGA) with a 10% probability of occurrence or exceedance in 50 years (475 year mean return period) for rock sites at the capitals of seven SOPAC countries. The miscellaneous sources in the figure for Fiji and Vanuatu are Jones (1998) and Suckale and Grünthal (2009), respectively. It can be seen that our PGA values (labeled by AIR in Figure 5) are higher than those calculated by the Global Seismic Hazard Assessment Program (GSHAP) (McCue, 1999) for the capitals of six countries (excluding Tuvalu). One reason for the low GSHAP values is that the GSHAP study used point sources to represent earthquake rupture areas for source-site distance calculation and ground motion analysis. In our model, the geometry of all sources is formulated by a three-dimensional rupture area. This will affect the calculation of the source-site distances, especially for sites close to large magnitude subduction zones. We evaluated the effect of the point source assumption on regional hazard estimates. The results indicate about 30% reductions in PGA values (labeled by

AIR point source in Figure 5) at the capitals of Fiji, Solomon Islands, Tonga and Vanuatu. This is because these cities are right on or very close to subduction zones, and rupture area of large subduction zone earthquakes cannot be neglected.

Our model clearly shows that the seismic hazard in Tonga is much higher than the seismic hazard in Tuvalu. In the GSHAP model, Tuvalu has similar hazard levels as Tonga. Tonga is in a subduction zone and experiences many events each year, while Tuvalu has experienced only one significant event in the past 100 years. This difference is correctly captured by the this study, but is apparently missed by the GSHAP maps. Finally, our estimate of the seismic hazard for Vanuatu and Fiji is consistent with the estimate in the study by Suckale and Grünthal (2009) and Jones (1998), respectively.



(a) (b) (c)

Figure 6. (a) Site condition maps of Port Vila, Vanuatu by characteristic resonant frequency; (b) expected PGA (g) with a 10% probability of exceedance in 50 years for Port Vila, Vanuatu, created by applying the site condition maps in (a); and (c) identical to (b) except point sources instead of three-dimensional rupture geometry for earthquakes are used in ground motion calcuations.

In addition to earthquake source characteristics and distance to the site, local site conditions have a very strong influence on earthquake ground motions, and therefore on seismic hazard and risk estimates. Shorten et al. (2001) have studied seismic microzonation by carrying out microtremor surveys for four capital cities: Suva, Fiji; Port Vila, Vanuatu; Honiara, Solomon Islands; and Nuku'alofa, Tonga. We implemented the site characteristics provided by Shorten et al. (2001) into the ground motion calculations. Figure 6(a) illustrates the microzonation map for Port Vila by Shorten et al. (2001). Figure 6(b) displays the estimated 475-year PGA values considering site conditions based on the microzonation map. It can be seen that the seismic hazard levels have strong correlation with site conditions. Figure 6(c) is identical to Figure 6(b) except using point sources instead of three-dimensional rupture geometry for earthquakes. Again, the seismic hazard is consistently reduced.

Discussion and Conclusions

One of the challenges in constructing a seismicity model for the SOPAC region lies in quantifying the rate of mega-thrust earthquakes with magnitudes of 8.5 and greater. There have not been any large events recorded in this region in the past 100 years; therefore, some the existing studies on the seismic hazard in this region do not consider such large earthquakes (Suckale and Grünthal 2009). However, we assumed that the lack of observational data is due to the shortness and incompleteness of the historical catalog and the very long recurrence of such large events. McCaffrey (2008) suggests that the lack of historical large magnitude earthquake on a large subduction zone should not rule out the possibility that the subduction one is capable of producing a magnitude 9 or larger earthquake. We estimate the rate of such earthquakes based on plate tectonics and the moment conservation principle at the first-order approximation. Further study is necessary to better quantify the magnitude-rate of such earthquakes.

A comparison between the hazard estimates from this study and the corresponding results from other studies indicates both similarities and large differences. Considering that the results presented in Figure 5 are produced by different groups at different time, we can attribute the observed differences in hazard to the differences in earthquake source models, attenuation relationships used for ground motion analysis, site conditions, site amplification analysis, and the detail of the hazard calculations. The largest differences happen for the case of using three-dimensional source geometry for the areas that are close to large subduction zones. The difference between our results and others reduces when we use the point source model. This is a clear indication of the importance of formulating realistic source geometry for large magnitude earthquakes for hazard analysis of sites close to those earthquakes. The importance of the source geometry issue is reduced for sites far from the sources of large magnitude earthquakes.

Site amplifications are also very critical in realistic seismic hazard study. For the regions that lack of soil maps and related studies, using high resolution topographic slope as a proxy for seismic site conditions and amplification has been proven to be a practical method (Wald and Allen 2007). In this study, we presented a detailed seismicity model which considers different type of earthquakes. The most recent attenuation relationships and site conditions based on microzonation studies are applied to obtain the seismic hazard for the region. Our seismic hazard model is more compatible with some of the local models than the GSHAP global model.

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