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RESEARCH ARTICLE

Regional ash fall hazard II: Asia-Pacific modelling results and implications

Susanna Jenkins · John McAneney · Christina Magill · Russell Blong

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Abstract In a companion paper (this volume), the authors propose a methodology for assessing ash fall hazard on a regional scale. In this study, the methodology is applied to the Asia-Pacific region, determining the hazard from 190 volcanoes to over one million square kilometre of urban area. Ash fall hazard is quantified for each square kilometre grid cell of urban area in terms of the annual exceedance probability (AEP), and its inverse, the average recurrence interval (ARI), for ash falls exceeding 1, 10 and 100 mm. A surrogate risk variable, the Population-Weighted Hazard Score: the product of AEP and population density, approximates the relative risk for each grid cell. Within the Asia-Pacific region, urban areas in Indonesia are found to have the highest levels of hazard and risk, while Australia has the lowest. A clear demarcation emerges between the hazard in countries close to and farther from major subduction plate boundaries, with the latter having ARIs at least 2 orders of magnitude longer for the same thickness thresholds. Countries with no volcanoes, such as North Korea and Malaysia, also face ash falls from volcanoes in neighbouring countries. Ash falls exceeding 1 mm are expected to affect more than one million people living in urban areas within the study region; in Indonesia, Japan and the Philippines, this situation could occur with ARIs less than 40 years.

Keywords Volcanic hazard · Hazard assessment · Probabilistic modelling · Ash dispersion · Regional hazard assessment · Modelling implications

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S. Jenkins · J. McAneney · C. Magill · R. Blong
Risk Frontiers, Macquarie University,
Sydney, NSW 2109, Australia

S. Jenkins (✉)
Now at Department of Earth Sciences, Wills Memorial Building,
University of Bristol,
Bristol BS8 1RJ, UK
e-mail: susanna.jenkins@gmail.com

R. Blong
AonBenfield Australia,
Sydney, NSW 2000, Australia

Introduction

This study employed probabilistic modelling techniques to undertake a regional assessment of ash fall hazard across the Asia-Pacific region. A companion paper (Jenkins et al. 2012) details the methodology and calculation of input variables, while this study focuses on application to the Asia-Pacific region. In total, hazard is evaluated for more than two billion people and one million square kilometre of urban area lying within 1,000 km of 190 volcanoes.

Figure 1 shows volcano locations and urban populations by latitude; Table 1 provides broad statistics for the number of volcanoes by country and urban areas at risk, both within and beyond national boundaries. For example, 306,308 km^2 of urban area lies within 1,000 km of South Korea's Halla volcano; however, only 4 %, or 11,754 km^2, of this is within South Korea, with the remaining urban areas split between eastern China, North Korea and Japan.

The spatial patterns of simulated ash dispersal and thickness are presented as annual exceedance probabilities (AEP) and average recurrence intervals (ARI) for critical ash thickness thresholds. The AEP is the estimated annual probability that ash accumulation will exceed critical thicknesses, while the ARI is the average expected time interval between ash falls of a given thickness or greater.

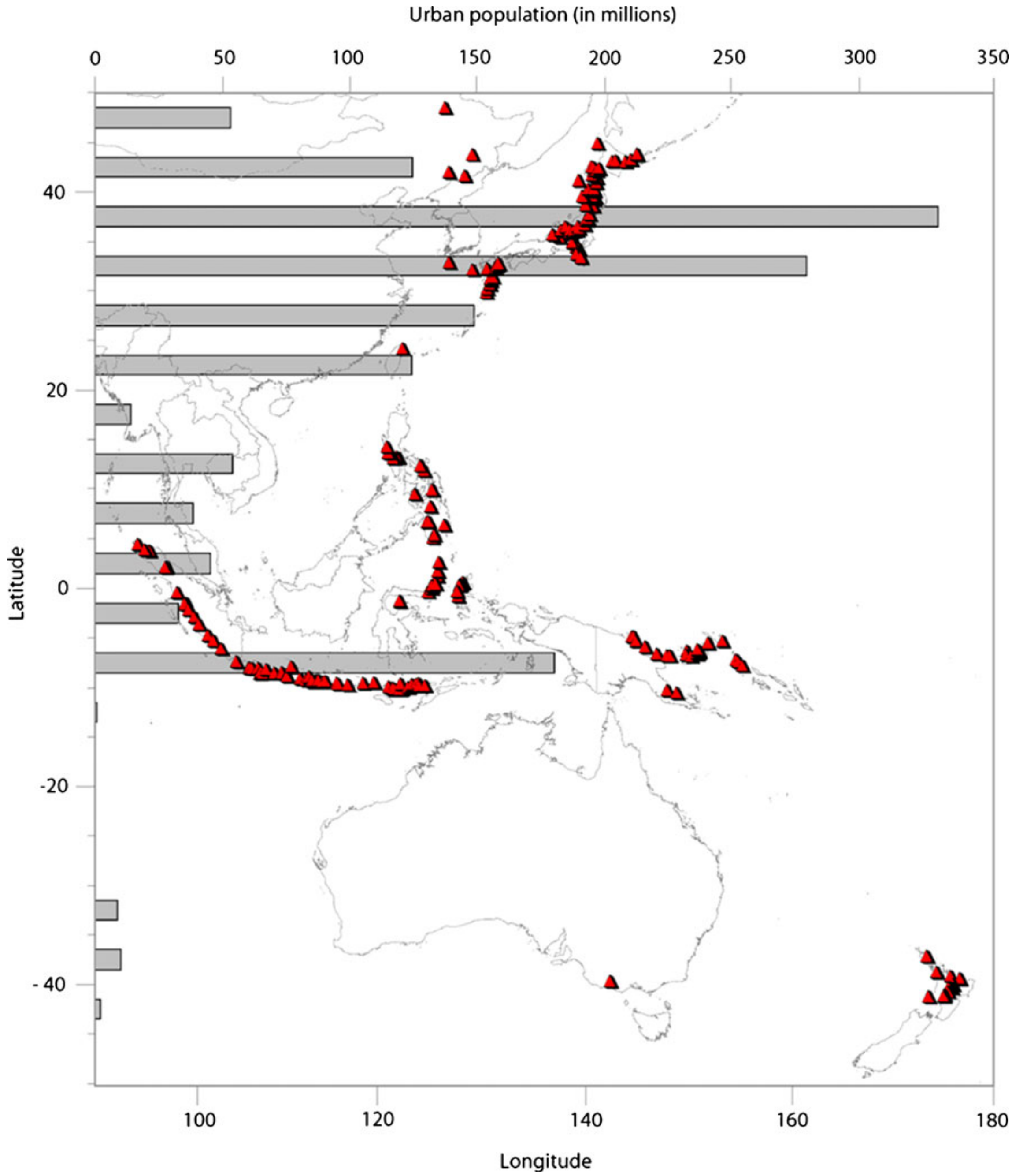

Fig. 1 Volcano locations in the Asia-Pacific region considered in this study, overlain with population counts within 1,000 km of each volcano and within 5° latitude bands. Population data derived from LandScan 2005 (Oak Ridge National Laboratory 2005)

A volcanic risk assessment must consider more than just the hazard. Strictly, risk is a function of hazard frequency and magnitude; the exposure expressed as the spatial distribution and numbers of elements at risk; the vulnerability of these elements to the hazard; and also, if risk is to be evaluated in monetary terms, their value (UN/ISDR 2002). Our study stops short of estimating risk in this manner; however, we do develop a surrogate risk variable obtained by weighting calculated AEP by impacted urban population densities. This new risk variable, termed the Population-Weighted Hazard Score (PWHS), allows us to assess whether the risk to impacted communities is more strongly controlled by the hazard or by population density. Acronym definitions are provided in Appendix 1.

Table 1 Number of volcanoes in each country against the total urban area lying within 1,000 km of the country's volcanoes and the proportion of that falling within each country's national boundaries

Country	Volcanoes	Total urban area (km^2) within 1,000 km of each country's volcanoes	Proportion of total urban area (%) within each country's boundaries
Indonesia	73	144,261	76
Japan	63	17,642	29
Papua New Guinea	21	2,572	64
Philippines	15	73,460	46
New Zealand	11	2,735	100
eastern China	4	389,064	100
South Korea	1	306,308	4
Taiwan	1	177,899	4
Australia	1	9,212	100

Summary of methodology

Overview

Using the ash advection–diffusion model ASHFALL (Hurst 1994), 1,000 eruption and ash dispersal scenarios were simulated for 190 volcanoes in the Asia-Pacific region (Fig. 1). Eruption magnitude–frequency relationships were developed for each volcano, based upon its eruption history and the globally averaged behaviour of analogous volcanoes. Eruption histories were drawn from the Smithsonian Institution catalogue of Holocene events (Siebert and Simkin 2002–) with global analogies taken to be those volcanoes of the same type classification—caldera, large cone, shield, lava dome, or small cone. Probability distributions were developed to describe the key hazard variables of eruption volume, column height, particle settling velocities, and altitude-varying wind speed and direction. Using stochastic simulation techniques, ash dispersion and the associated probability of occurrence were calculated for urban areas within 1,000 km of each volcano at a resolution of 1 km^2. Only eruptions with a Volcanic Explosivity Index (VEI) of 4 or greater, corresponding to a minimum bulk volume of 0.1 km^3 (Newhall and Self 1982), were simulated. For further details, the reader is referred to Jenkins et al. (2012).

Ash thickness thresholds

Thickness thresholds of 1, 10 and 100 mm were chosen as signalling the onset of various degrees of damage and disruption to communities. An ash fall of 1 mm may lead to airport closure; contamination of water supplies; corrosion and short circuiting of electrical appliances; disruption of road, rail and air transport; and respiratory problems (Baxter 1990; Blong 1984). As well as aggravating these same impacts, an ash thickness of 10 mm may begin to cause minor structural damage for weaker building components and result in significant crop and vegetation damage, with most pastures destroyed under accumulations of 50 mm (GNS Science 2006). Significant lifeline disruption would occur, with major clean-up activities being required for ash thicknesses greater than 100 mm. This threshold also marks the onset of partial or total collapse of some buildings (Blong 1984).

Population density

The distribution and density of population was derived from the modelled ambient population dataset, LandScan 2005 (Oak Ridge National Laboratory 2005). These data, compiled on a 30 arc sec grid (approximately 1 km at the equator), are sourced from census counts and contextual information such as the proximity of roads, topography, land cover and night-time lights (Fig. 2). For our purposes, and in the absence of an internationally agreed definition, an urban area is defined as having a population density in excess of 400 people/km^2, comprising more than one million square kilometre in the Asia-Pacific region. Within the study region, nearly 10 % of areas defined to be urban have relatively low population densities of between 400 and 450 people/km^2. The distribution of population between countries is shown in Table 2.

Population-Weighted Hazard Scores

A risk variable, the PWHS, is determined from the product of AEP and Population Density (PD). The PWHS is calculated for each grid cell x and for each ash thickness threshold (z) and allows us to identify areas of particularly high, or low, risk.

Results and discussion

Results for impacts from large magnitude (VEI≥4) eruptions are presented in the following sections. The reader is reminded that these estimates are calculated at ash thickness thresholds of 1, 10 and 100 mm and refer only to urban areas (≥400 people/km^2) within 1,000 km of assessed volcanoes.

Ash fall hazard

Ash fall hazard for each grid cell is expressed as the ARI, the approximate inverse of AEP, for each thickness threshold

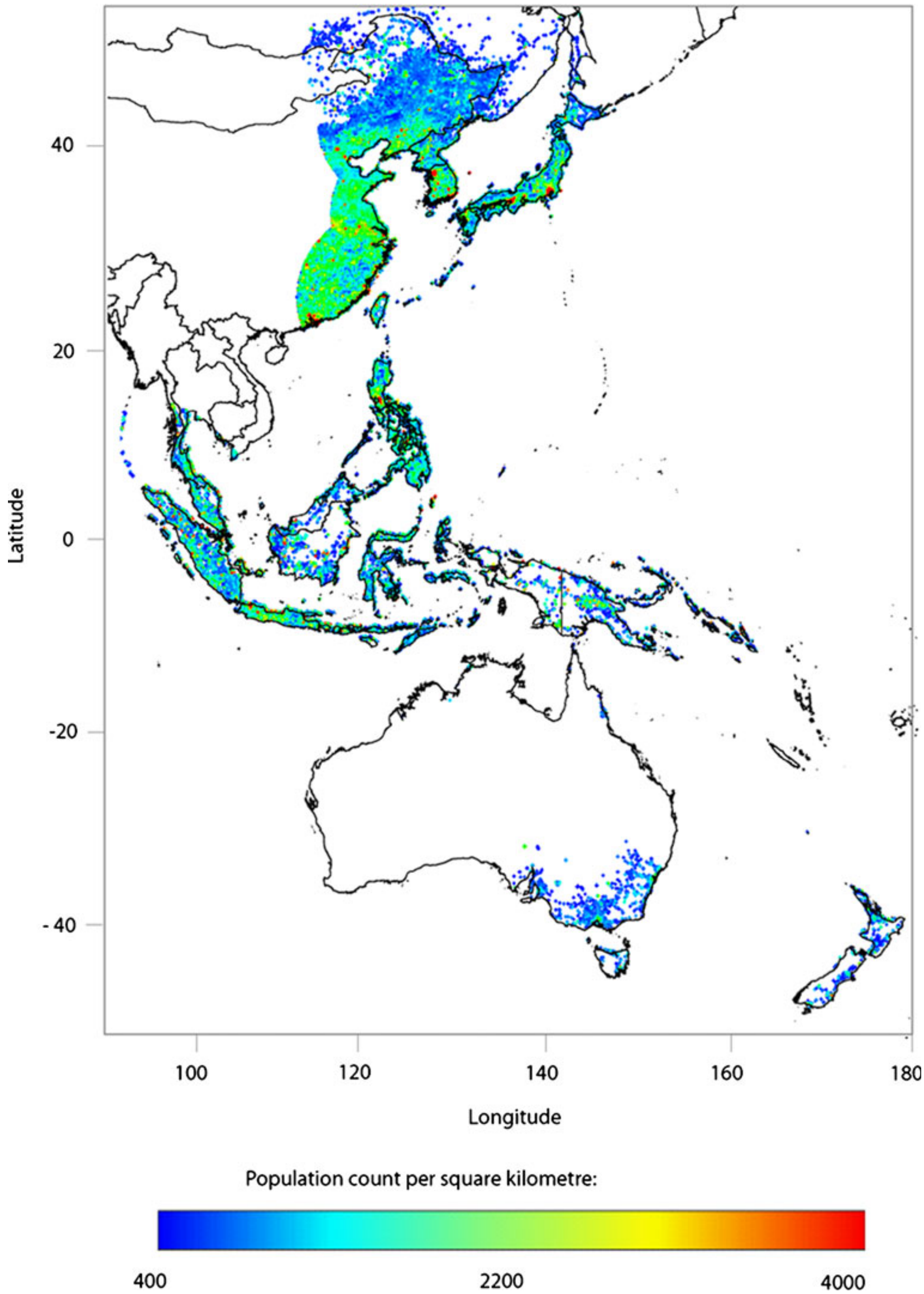

Fig. 2 Population density across the Asia-Pacific region (Source: LandScan 2005 database (Oak Ridge National Laboratory 2005)) on a 1 km^2 grid for areas within 1,000 km of a study volcano

(Fig. 3). These values take into account ash thickness and eruption probabilities associated with each simulation capable of impacting that cell. The range of ARIs across the region is large: with minimum values (highest hazard frequency) for exceeding 1 mm of 29 years near Kelut volcano in Java, Indonesia and values between 50 and 80 years in parts of New Zealand, Papua New Guinea and the Philippines. The lowest hazard is found in eastern Russia with a negligible AEP that equates to an ARI in excess of 100 Myr. These values are a consequence of both low eruption frequencies associated with volcanoes capable of impacting the grid cell and the low probability of simulated eruptions impacting the area—the nearest volcano (Rishiri) being over 400 km to the south and producing only one simulation that impacts the location.

Parts of Indonesia, Papua New Guinea, New Zealand, Japan and the Philippines are characterised by ARIs of less than 200 years, even for ash thickness exceeding 100 mm. This is understandable given their tectonic setting in relation

Table 2 Number of volcanoes analysed within each country, total urban population lying within 1,000 km of these volcanoes, the proportion of this within the country itself and the mean and range of the population density to the nearest 100

Country	Number of volcanoes	Total urban population (millions) within 1,000 km of each country's volcanoes	Proportion of total urban population (%) within national boundaries	Population density mean	Population density range
Indonesia	73	314	75	2,174	400–91,500
Japan	63	494	34	2,844	400–131,800
Papua New Guinea	21	5	64	1,854	400–45,500
Philippines	15	212	40	2,890	400–160,600
New Zealand	11	5	100	1,809	400–13,800
eastern China	4	763	99	1,961	400–84,600
South Korea	1	712	9	2,326	400–131,800
Taiwan	1	474	6	2,664	400–160,600
Australia	1	17	100	1,795	400–36,400

to major subduction plate boundaries where we expect to find more volcanoes, more frequent eruptions and more explosive eruption styles (Francis and Oppenheimer 2004; Simkin and Siebert 1994). Countries farther from major subduction zones and with only a small number of volcanoes, such as Australia, eastern China, South Korea and Taiwan, show ARIs far in excess of 10,000 years, even for thickness thresholds of only 1 mm. Urban areas in countries such as Malaysia and North Korea may also be at risk from ash falls up to and exceeding 100 mm in thickness, despite having no assessed volcanoes within their boundaries, albeit with a minimum ARI of approximately 2,400 years in the case of North Korea. Due to the large spatial extent relative to volcanic hazards such as pyroclastic flows and lahars, ash falls are likely to be the only primary volcanic hazard experienced in these countries.

The mean values of ARI for each country (Fig. 4) are approximately equal to the corresponding standard deviation for all thickness thresholds studied, consistent with an exponential distribution of the hazard and with the tail representing low frequency, high magnitude eruptions. Increasing the ash thickness threshold 2 orders of magnitude, from 1 to 100 mm, results in the expected ARI averaged over all grid cells in the country, increasing approximately fourfold and therefore reflecting the simulated power law

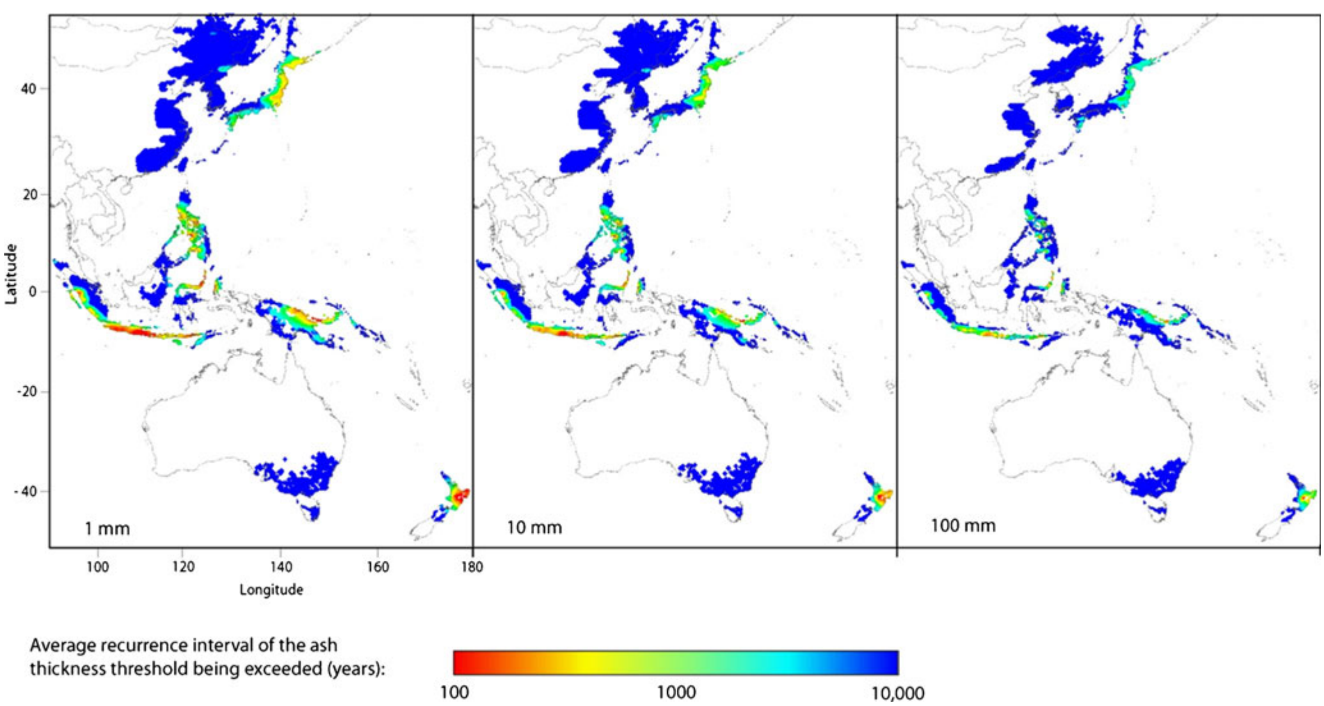

Fig. 3 Average recurrence intervals (ARI) for ash thicknesses exceeding 1, 10 and 100 mm across the Asia-Pacific region

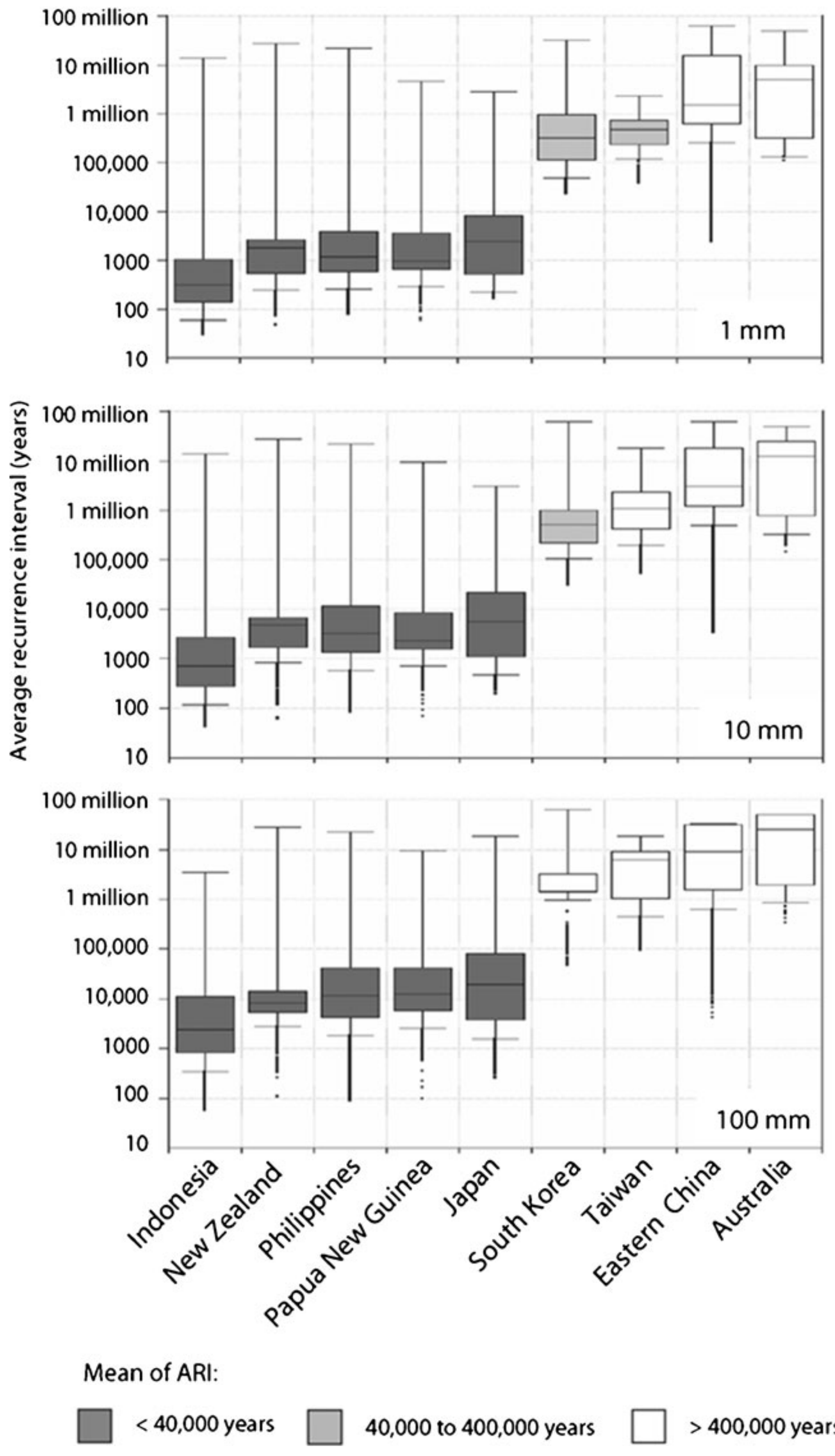

Fig. 4 *Box plots* describe the statistical distribution of average recurrence intervals (ARIs) across urban grid cells within each country, for ash thicknesses exceeding 1, 10 and 100 mm. The *box and internal line* represent the interquartile range and median with the ends of the whiskers representing minimum and maximum values and outliers represented by points. Mean ARI is indicated by *box shade*

relationship between eruption magnitude and frequency (Fig. 4). The mean country ARI for ash thickness exceeding 1 mm ranges from as low as 196 years (Indonesia) to 787,000 years (Australia), with countries close to subduction zones possessing a national mean ARI approximately 3 orders of magnitude smaller than those farther away (Fig. 4). Mean ARIs of 191,000 and 322,000 years for South Korea and Taiwan result in part from the close proximity of the grid cells to Japan. Of the 841 simulated eruptions that resulted in ash falls greater than 1 mm in Onpyong-ni, the location of maximum hazard in South Korea, 95 % are from Halla, South Korea's only volcano; however, the remaining 5 % (arising from nine Japanese volcanoes) each impact the cell with nearly an order of magnitude greater probability . Thus, if we were to consider impacts from only volcanoes nationally, the ash hazard would be underestimated.

Table 3 Location co-ordinates, population density and number of volcanoes impacting the grid cell exhibiting minimum average recurrence interval (largest hazard) in each country, calculated for each thickness threshold

Country	Location of the minimum ARI (in years) for ash thicknesses exceeding:						
	Location		Population density	Number of volcanoes implicated	1 mm	10 mm	100 mm
Indonesia	112.27 E, 7.98 S	Malang	485	22	29	40	57
New Zealand	175.81 E, 38.99 S	Turangi	578	11	47	60	105
Papua New Guinea	148.33 E, 5.58 S	Sagsag	559	17	59	120	220
Philippines	124.02 E, 12.75 N	Legaspi	502	5	78	81	87
Japan	140.53 E, 38.15 N	Shiroishi	743	46	160	190	250
Eastern China	128.94 E, 42.08 N	Musan	1,524	3	2,410	1,740	2,400
South Korea	126.79 E, 33.39 N	Onpyong-ni	1,211	11	23,000	34,000	56,100
Taiwan	121.81 E, 24.79 N	Yilan	782	1	38,000	51,700	93,500
Australia	143.08 E, 37.82 S	Pura Pura	456	1	110,000	144,900	335,600

Countries are ordered by increasing ARI expected for ash thicknesses exceeding 1 mm. Location co-ordinates refer to the 1 mm thickness threshold but are approximately similar (within 2°) for 10 and 100 mm thresholds

The minimum ARI for each ash thickness threshold denotes the maximum hazard. Table 3 shows the location of maximum hazard for each country and indicates where further, more detailed analysis of individual volcanoes and community vulnerability may be warranted. The maximum hazard occurs at approximately the same location for each thickness threshold and typically coincides with rather modest population densities of less than 800 people/km^2.

A greater number of volcanoes potentially impacting the grid cell of maximum hazard does not noticeably decrease the ARI (Table 3). This is expected as small recurrence intervals are likely dominated by a single volcano close by. For example, the point of maximum ash fall hazard (>1 mm) for urban areas in the Philippines, with an ARI of 78 years, lies approximately 8.5 km southwest of Mayon volcano. While there are nine other volcanoes within 500 km with the potential to impact this grid cell and a further five within 1,000 km, hazard outcomes are dominated by Mayon. In addition, local communities may also expect ash falls from more frequent, smaller eruptions of VEI 3 or less that have not been simulated here.

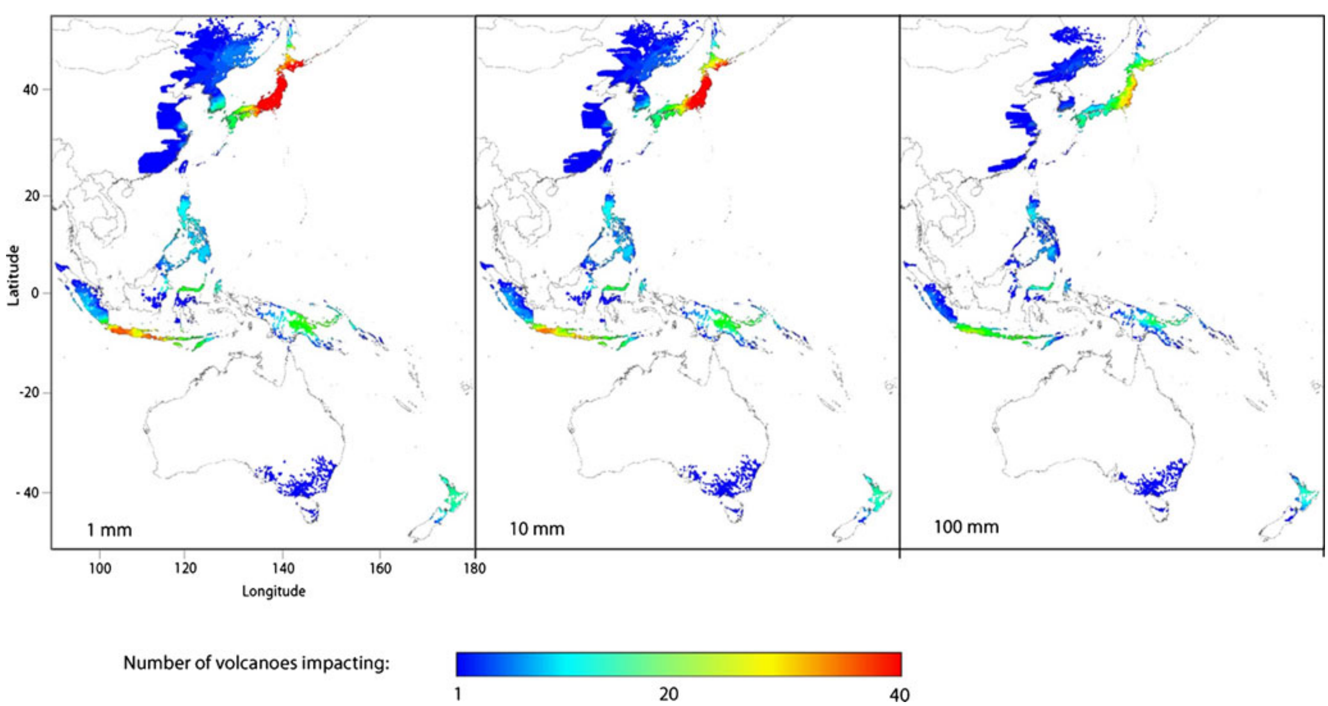

Fig. 5 Number of volcanoes impacting each cell across the region, at ash thickness thresholds of 1, 10 and 100 mm

Multiple volcano impacts

The AEP and ARI at any given grid cell reflect the probability of exceeding ash thickness thresholds from all volcanic sources capable of impacting that cell. A map of the number of volcanoes impacting each grid cell for each thickness threshold is shown in Fig. 5. This does not distinguish which volcanoes have the greatest impact, with the hazard for many grid cells dominated by one or a small subset of volcanoes. Nonetheless, it does highlight areas susceptible to falls from distal sources which may have been previously unappreciated.

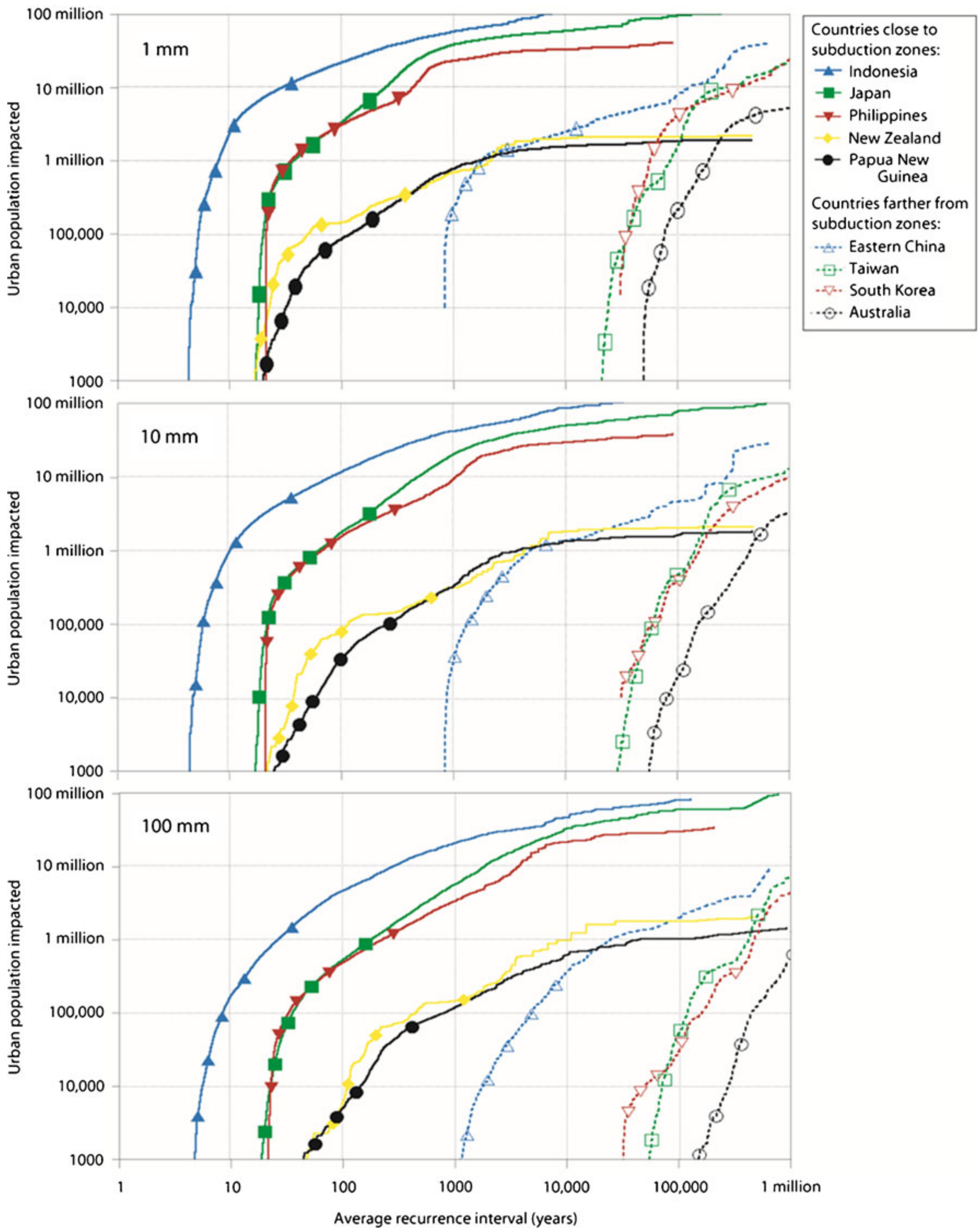

Fig. 6 Average recurrence interval against urban population impacted by volcanoes from that country for the Asia-Pacific region

Our simulations suggest that eruptions from 43 different volcanoes are capable of generating ash thicknesses exceeding 1 mm in Tokyo; yet, given an eruption occurring; only three of these—Fuji, On-Take and Hakone—have a 20 % or greater chance of impacting the city. At each of the remaining 40 volcanoes, less than 200 of the 1,000 simulations produce ash falls exceeding 1 mm in Tokyo.

Urban areas in Japan stand out as the most threatened by ash falls from multiple volcanoes (Fig. 5): north-eastern parts of Honshu, for example, may expect impacts from more than 30 volcanoes, even when considering accumulations of ash exceeding 100 mm. Despite the higher number of volcanoes in Indonesia (n=73), compared to Japan (n=63), ash falls from a maximum 15–20 separate volcanoes may be expected in parts of Java for thicknesses above 100 mm. These differences are a consequence of predominant wind directions in relation to the orientation and size of each country. For example, a large number of volcanoes in Honshu lie on its western side and thus the highest areas of population on the east of the island are downwind, given the predominance of westerly winds at tropopause altitudes (~11 km). In spite of these dominant westerly winds, parts of South Korea and eastern China may be susceptible to ash falls from Japanese volcanoes during certain seasons and when high (>20 km) plumes are exhibited.

Urban population impacted

The urban populations impacted at each ash thickness threshold, as a function of ARI, are given in Fig. 6. Most countries show a similar trend, characterised by a rapid rise in impacted urban populations with increasing ARI and then saturation at long ARIs. Papua New Guinea and New Zealand, which exhibit the lowest population densities of the more hazardous countries, show a more gradual increase in slope.

Volcanoes in Indonesia have the potential to affect the greatest number of people, with the possibility of impacting more than two million people with more than 1 mm of ash on average every decade (Table 4). In New Zealand, on the other hand, no urban population is at risk to more than 1 mm on average every decade and only 142,000 people every century. Indonesia, with the largest number of volcanoes, is the only country for which urban populations are expected to be impacted as frequently as every decade by ash thicknesses up to and exceeding 100 mm. While Japan has only slightly less volcanoes than Indonesia, 63 versus 73, it does have a larger exposed urban population, 494 million versus 314 million (Table 2), and so we may expect the hazard to be comparable. However, Japan is in fact comparable with the Philippines, a country with less than one quarter of the volcanoes and half the population. Population density decreases sharply with distance from active volcanoes in Southeast Asia, but increases with distance in Japan (Small and Naumann 2001). This difference is likely due to climatic (elevated areas in tropical climates offering a more habitable climatic range relative to tropical lowlands) and cultural factors (agrarian populations dominate fertile volcanic areas, while industrial and post-industrial populations are concentrated in large urban areas, often along coasts).

For all countries considered here, urban populations in excess of one million could plausibly be impacted by ash thicknesses exceeding 1 mm. In Indonesia, this may be expected on average every 8 years while for Australia our modelling suggests a very small probability and ARI of 191,000 years (Fig. 7). Of countries farther from subduction zones, the four volcanoes in eastern China are expected to affect the greatest number of people with the greatest frequency (Fig. 6), with simulations showing one million people in urban areas impacted on average every 1,850 years by thicknesses exceeding 1 mm. Volcanoes in Taiwan, South Korea

Table 4 Approximate population impacted (in thousands) at ash thicknesses greater than 1, 10 and 100 mm, for volcanoes in each country and for ARI of 10, 100 and 1,000 years

	10 years			100 years			1,000 years		
	1 mm	10 mm	100 mm	1 mm	10 mm	100 mm	1 mm	10 mm	100 mm
Indonesia	2,100	860	150	20,500	10,900	4,500	53,700	39,700	20,100
Japan	–	–	–	3,100	1,700	500	35,900	19,200	5,500
Papua New Guinea	–	–	–	85	35	5	760	320	120
Philippines	–	–	–	2,900	1,500	470	21,900	8,800	3,200
New Zealand	–	–	–	140	80	6	670	310	140
eastern China	–	–	–	–	–	–	210	30	–
South Korea	–	–	–	–	–	–	–	–	–
Taiwan	–	–	–	–	–	–	–	–	–
Australia	–	–	–	–	–	–	–	–	–

(–) reflect no simulated ash fall hazard at that particular ARI and thickness threshold

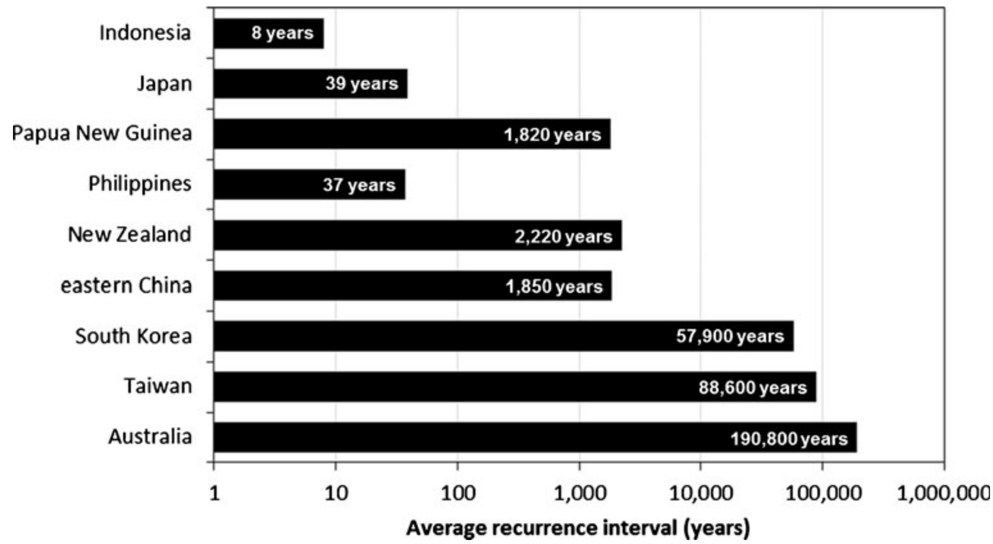

Fig. 7 Average recurrence interval expected within each country from volcanoes in that country for ash thicknesses exceeding 1 mm impacting one million people within urban areas. Countries are ordered with a decreasing number of volcanoes, from Indonesia (73) to Australia (1)

and Australia can be expected to impact similar numbers of people much less frequently, with simulations showing one million people affected approximately every 58,000 years by Halla (South Korea), 89,000 years by Kueishantao (Taiwan) and 191,000 years by the Newer Volcanic Province (Australia).

For one million urban dwellers to be affected in each country, the ARI for thicknesses exceeding 1 mm generally increases as the number of volcanoes decrease; however, the relationship is modulated by eruption frequency and population density. The Philippines, for example, with 15 volcanoes shows a relatively small ARI of 37 years, while Papua New Guinea, with 21 volcanoes, shows a comparatively long ARI of 1,818 years. This is largely a reflection of urban population densities in the Philippines, with a mean of 2,890 people/km^2 compared with 1,854 in Papua New Guinea.

Population-Weighted Hazard Scores

The PWHS weights the AEP for a given location and thickness threshold by PD for that grid cell. If locations of maximum AEP (0.03) and maximum PD (160,618) across the region were to coincide, PWHS would equal 4,509; however, this is not the case and typically PWHS are <10 (Fig. 8). For thicknesses exceeding 1 mm, areas close to

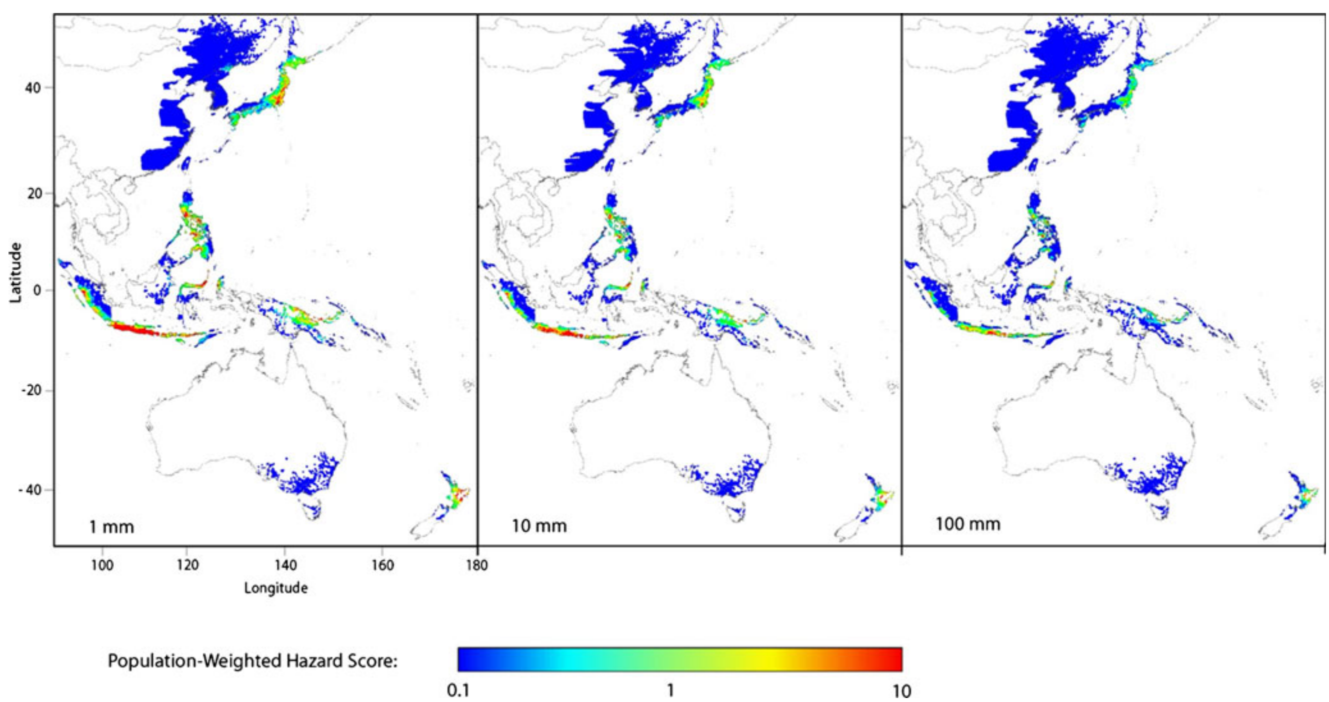

Fig. 8 Population-weighted hazard scores across the Asia-Pacific region, for ash thicknesses exceeding 1, 10 and 100 mm

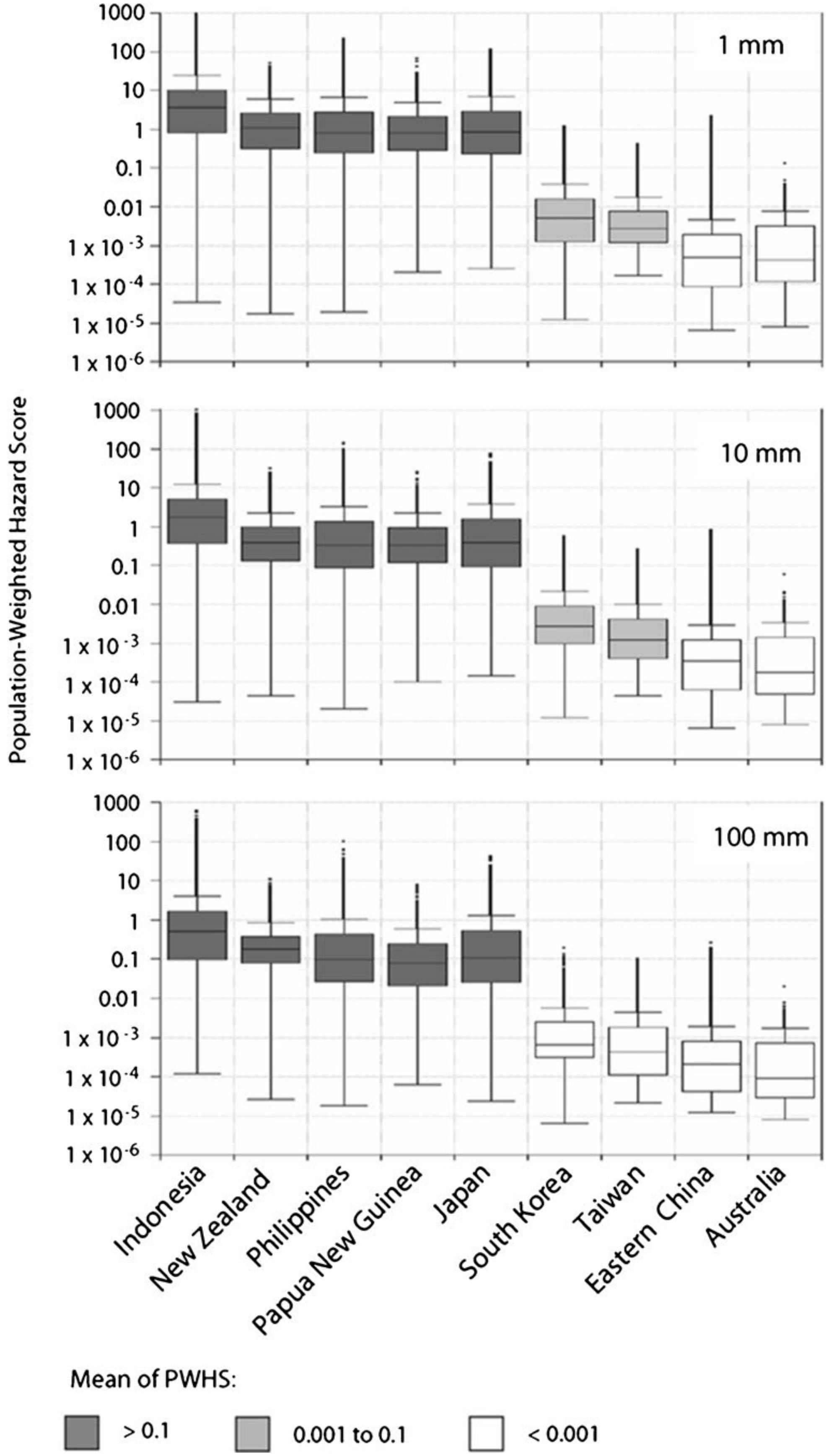

Fig. 9 *Box plots* describe the statistical distribution of PWHS across urban grid cells for each country, for ash thicknesses exceeding 1, 10 and 100 mm. The box represents the interquartile range with the *ends of the whiskers* representing minimum and maximum values and outliers represented by *points*. Mean PWHS is indicated by *box shade*

Table 5 Location co-ordinates, population density and number of volcanoes impacting the grid cell exhibiting the maximum population weighted hazard scores in each country, calculated for each thickness threshold

Country	Location of the maximum population weighted hazard scores For ash thicknesses exceeding:						
	Location		Population density	Number of volcanoes	1 mm	10 mm	100 mm
Indonesia	112.63 E, 7.96 S	Malang	84,340	22	2,169.00	1,454.00	598.00
Philippines	120.95 E, 14.65 N	Manila	126,370	7	219.00	140.00	100.00
Japan	140.87 E, 38.28 N	Sendai	27,600	46	116.00	78.00	42.00
Papua New Guinea	143.69 E, 3.56 S	Wewak	8,400	11	56.00	23.00	8.00
New Zealand	176.08 E, 38.68 S	Taupo	3,960	11	52.00	40.00	12.00
eastern China	129.50 E, 42.89 N	Yanbian	29,750	3	2.20	0.79	0.26
South Korea	128.97 E, 35.11 N	Pusan	76,380	12	1.20	0.53	0.20
Taiwan	121.53 E, 25.04 N	Taipei	63,900	1	0.41	0.26	0.10
Australia	144.89 E, 37.72 S	Melbourne	36,430	1	0.13	0.06	0.02

Countries are ordered in decreasing PWHS expected for ash thicknesses exceeding 1 mm. The location co-ordinates refer to the 1 mm thickness threshold but are approximately similar (within 4°) for 10 and 100 mm thresholds

Kelut volcano, Indonesia, have the shortest ARI (largest AEP) at 29 years, but this is coupled with relatively modest PDs (400–500/km^2). Japan, Indonesia, Papua New Guinea, Philippines and New Zealand all have relatively high PWHS, with some locations exceeding 10 (Fig. 8). Higher scores are dominated by high hazard, e.g. northern Papua (ARI<100 years), high population densities, e.g. eastern China (>4,000 people/km^2), or in some cases a combination of high hazard and high population densities as is the case for metropolitan Manila (maximum PWHS of 219). For a 1 mm threshold, the PWHSs range from a minimum 4.74×10^{-6} near Vanino in eastern Russia to a maximum of 2,170 in Malang, Indonesia.

The high score in Malang is a consequence of an ARI of 40 years, arising from 22 separate volcanoes, and an urban population density of 84,344 people/km^2. South Korea and eastern China exhibit relatively high scores because of their high population densities, with mean densities of 2,326 and 1,961 people/km^2, respectively (Table 2).

Across the study region, the PWHS shows a similar distribution to the hazard, with countries close to major subduction zones showing higher values (Figs. 8 and 9), with mean country scores between 2.16 (Papua New Guinea) and 10.99 (Indonesia). Population densities at locations of maximum PWHS in each country range from 3,958 people/km^2 in Taupo, New Zealand to 126,366 people/km^2 in Manila, Philippines (Table 5).

Locations of maximum hazard, population density and PWHS are mapped for each country, with those for Indonesia, Japan and the Philippines shown in Fig. 10. There appears to be little correlation between population density and hazard. Logically, the points of maximum population density and hazard need not coincide: while the agricultural benefits of ash falls may encourage smaller populations to live close to volcanoes, larger urban populations are less likely to become established in areas where the hazard is relatively high. In densely populated volcanic countries with limited land area, such as Taiwan and the Philippines, the concurrence of high hazard and high population density will inevitably be greater than more sparsely populated countries with few volcanoes such as Australia. Maximum PWHS in Taiwan and the Philippines is found in the capital cities of Taipei and Manila; a consequence of high population densities, relatively high hazard and limited land area.

For the three countries exhibiting the highest PWHS in the region (Table 5), Indonesia, the Philippines and Japan, we show calculated hazard curves for the locations of maximum hazard, population density and PWHS (Fig. 10). These are built upon ARI values for each thickness threshold and offer a view of the hazard at each location. For Japan, the location of maximum population density (38,734 people/km^2) is in Greater Tokyo and the hazard curves show that ash thicknesses exceeding 1 mm may be expected every 502 years. By comparison, with maximum population densities of 91,492 and 16,618 people/km^2 in Jakarta and Manila, ash thicknesses exceeding 1 mm may be expected every 987 and 578 years, respectively. When considering the location of maximum PWHS, Indonesia shows the shortest ARI at 39 years (≥1 mm), with Japan and the Philippines showing larger ARI of 238 and 578 years, respectively. High population densities in the areas surrounding maximum hazard in Indonesia and Japan lead to close correspondence between the locations of maximum PWHS and maximum hazard (Fig. 10). The ARIs for ash thicknesses exceeding 1 mm, ordered from shortest to longest, at each of the locations of maximum values are shown in Table 6.

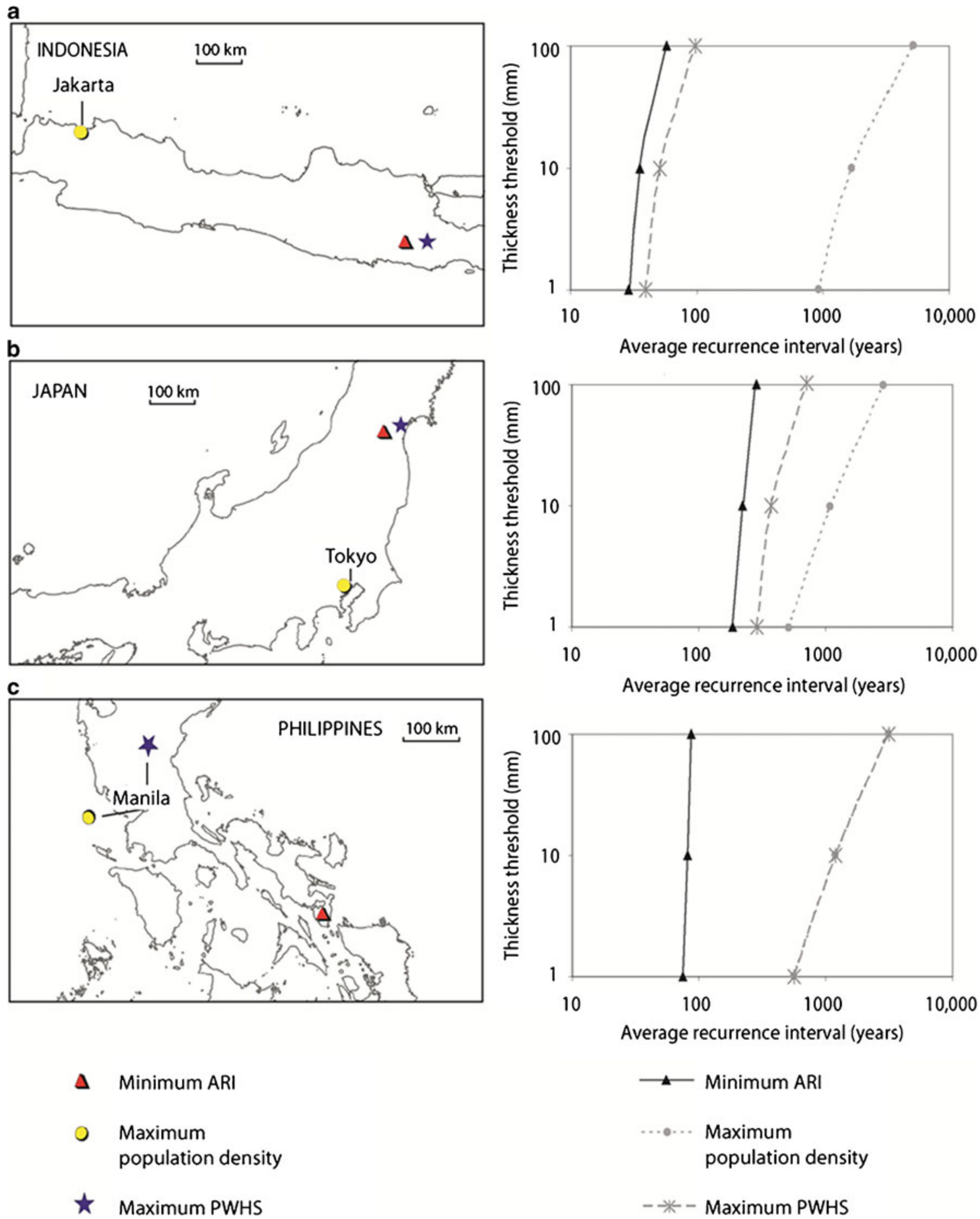

Fig. 10 The location of minimum ARI (*triangle*), maximum population density (*circle*) and maximum PWHS (*star*) and the associated hazard curves at each location for **a** Indonesia, **b** Japan and **c** Philippines

Concluding comments

In simulating ash fall hazard across the Asia-Pacific region, this study is the first of its kind. To account for variations in ash dispersal due to varying eruption magnitude and wind conditions, we employ ash advection–diffusion modelling. Rather than being volcano- or location-centric, the probabilistic methodology employed here allows a rapid appreciation of the hazard and numbers of people potentially at risk in urban areas across the region.

Indonesia has the highest hazard and population-weighted hazard scores while Australia has the lowest. This is a

Table 6 ARI for ash thicknesses exceeding 1 mm in Indonesia, Japan and the Philippines at the locations of maximum hazard, population density and PWHS

Maximum hazard		Maximum population density		Maximum PWHS	
Country	ARI	Country	ARI	Country	ARI
Indonesia	29	Japan	502	Indonesia	39
Philippines	78	Philippines	578	Japan	238
Japan	163	Indonesia	987	Philippines	578

Countries are ordered from shortest ARI to longest

reflection of the number of volcanoes capable of impacting each country, the frequency–magnitude relationship of each volcano and the distribution and density of exposed populations. Indonesia has 73 volcanoes, which are predominantly large cones, with a median ARI of 550 years for an eruption of VEI 4 or greater and a mean urban population density of 2,174 people/km^2. Australia, by comparison, contains only one small cone volcano with an ARI of approximately 32,700 years for an eruption of VEI 4 or greater and a lower mean urban population density of 1,795 people/km^2.

As expected, countries can be broadly grouped into those close to major subduction plate boundaries—Indonesia, Japan, Papua New Guinea, Philippines and New Zealand—and those farther away—eastern China, South Korea, Taiwan and Australia. For ash thicknesses exceeding 1 mm, mean ARIs are approximately 2–3 orders of magnitude shorter for the more hazardous countries (approximately 195–1,010 years), compared to the less hazardous countries (approximately 190,800–787,400 years). All countries can expect an approximately fourfold increase in ARI for ash thicknesses exceeding 100 mm, compared to those expected for thicknesses greater than 1 mm. The shortest ARI in the region at 29 years, for ash thicknesses exceeding 1 mm, can be found close to Kelut volcano in Indonesia, while Malang in Indonesia exhibits the greatest population-weighted hazard score, with a value of 2,169, which is around an order of magnitude greater than the median PWHS in Indonesia. As well as providing the shortest ARI (greatest hazard) and largest PWHS (greatest risk), volcanoes in Indonesia are expected to impact urban populations most frequently, with an estimated one million people affected on average every 8 years.

The hazard assessment methodology presented here can be adapted to provide estimates of expected ash thicknesses experienced at given exceedance probabilities, or over a given time period for comparison between different natural perils (e.g. The Global Seismic Hazard Assessment of Chen et al. 1998). The methodology can also be expanded to other areas and modified to assess volcanic perils other than ash fall. To gain a more comprehensive picture of risk, the relative vulnerability of populations and/or the value of elements at risk would need to be incorporated.

Some of the more hazardous areas in Japan, where thicknesses are expected to exceed 1 mm on average every 300–400 years, are concentrated around the Greater Tokyo area, the world's most populous metropolitan area (United Nations Statistics Division 2007). Including Tokyo, the study region is home to at least six urban agglomerates of over 10 million people. Of these six, Tokyo, Manila and Jakarta are at greatest risk from volcanic ash fall. More in-depth assessments may be justified for these cities, which along with improved local information on the eruptive behaviour of key volcanic sources, may lead to a greater understanding of this risk. Nonetheless, in highlighting countries of relatively high or low hazard together with population exposure, our study should prove useful to international aid agencies, insurance companies and large corporations for prioritising resources and as an initial overview of risk from this threat.

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Appendix 1: Definition of acronyms

AEP	Annual exceedance probability
ARI	Average recurrence interval—approximate inverse of annual exceedance probability
ASHFALL	Semi-analytical two-dimensional ash dispersion model developed by GNS Science, New Zealand
PD	Population density per square kilometre
PWHS	Population-weighted hazard score: the product of AEP and PD
VEI	Volcanic explosivity index

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