Mapping Earthquake Risk of the World

Man Li, Zhenhua Zou, Guodong Xu, and Peijun Shi

1 Background

In the program of Global Natural Disaster Hotspots, jointly conducted by Columbia University and the World Bank, mortality rate and economic loss rate caused by earthquake disaster are calculated as vulnerability coefficient based on mortality and economic losses in the historical earthquake records. Then the vulnerability coefficient is adjusted by earthquake density which is measured by earthquake frequency to estimate mortality risk and economic loss risk in the world (Dilley et al. 2005). In the program of Global Risk and Vulnerability Index Trends per Year (GRAVITY), hosted by the United Nations Environment Programme (UNEP)/European Global Information Resource Database, the vulnerability of earthquake is calculated based on hazard intensity, death toll, and so on in the historical earthquake records and combined with other economic indicators to establish loss function, to estimate annual average expected losses (Peduzzi et al. 2009). These two programs are the most influential natural disaster risk assessment projects. However, in the Global Natural Disaster Hotspots, loss rate of all previous earthquakes in the same region is used to represent both hazard and vulnerability, which cannot reflect spatial differences of risk, caused by spatial distribution differences of hazard and vulnerability. Therefore the programs are only be used for risk assessment at national level. The assessment results of GRAVITY are also at national level, which cannot demonstrate the risk differences within the country and region. Meanwhile, both programs take GDP as exposure for the assessment of economic losses, which describes economic flow. However, the earthquake imposes direct impact on economic stocks, which is quite different from economic flow.

Therefore, building vulnerability table at national scale and possibility of mortality caused by building collapse shall be taken into consideration to construct population vulnerability table. Combined with population density data and earthquake intensity, world earthquake mortality risk can be assessed. Meanwhile, social wealth shall be taken as social and economic exposure instead of GDP to assess world earthquake economic loss risk. Based on the above conceptions, the earthquake risk of the world is reassessed and mapped in this study at grid, comparable-geographic unit and national levels.

Mapping Editors: Jing'ai Wang (Key Laboratory of Regional Geography, Beijing Normal University, Beijing 100875, China) and Chunqin Zhang (School of Geography, Beijing Normal University, Beijing 100875, China).
Language Editor: Lianyou Liu (Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education, Beijing Normal University, Beijing 100875, China).

M. Li · Z. Zou
Academy of Disaster Reduction and Emergency Management, Ministry of Civil Affairs and Ministry of Education, Beijing Normal University, Beijing 100875, China

G. Xu
Disaster Prevention Institute of Science and Technology, Beijing 101601, China

P. Shi (✉)
State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
e-mail: spj@bnu.edu.cn

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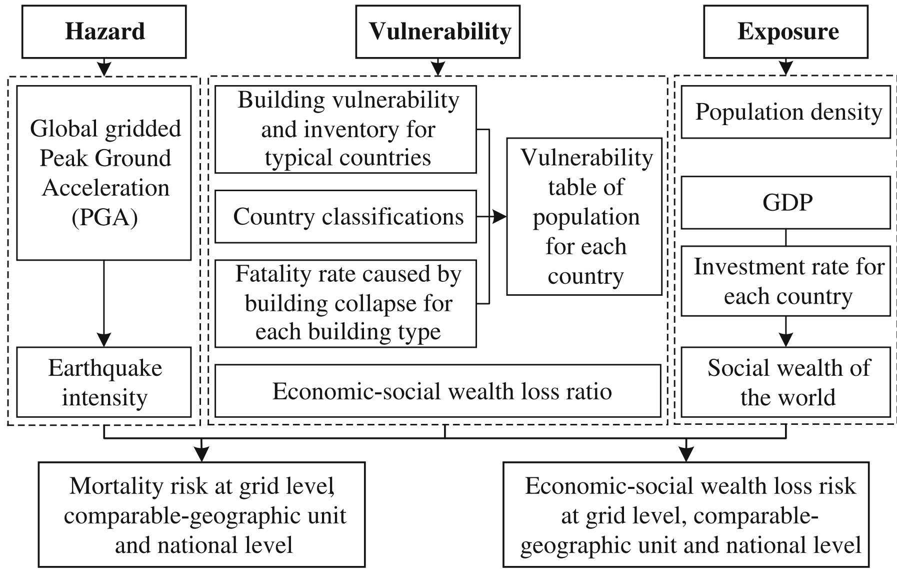


Fig. 1 Technical flowchart for mapping earthquake risk of the world

2 Method

Figure 1 shows the technical flowchart for mapping earthquake risk of the world.

2.1 Mortality Risk

2.1.1 Population Vulnerability Table at National Level

This study utilizes building vulnerability table (Appendix III, Exposures data 3.6) and mortality probability due to building collapse to establish population vulnerability at national level. The building vulnerability table includes two parts: building types in each country and their collapse probabilities caused by earthquake with intensity over V level; proportion of resident population in buildings of each type, including urban and rural population. Take the United Kingdom (UK) as an example, as shown in Table 1, for unreinforced brick masonry in mud mortar, the collapse probability by earthquakes with intensity of IX, VIII, VII, and VI are 15 %, 4 %, 0.6 %, and 0 %, respectively. Proportions of population in such buildings in urban and rural areas are 35 % and 50 %, respectively.

Fatality ratio caused by collapse of 8 types of common buildings is the empirical data applied to prompt loss assessment obtained by USGS (Appendix III, Exposures

Table 1 Building construction vulnerability and inventory of the UK

Construction material	Construction subtype	Probability of collapse (%) of building type when subjected to the specified shaking intensity				Fraction of population who lives in this building type	
		IX (0.65–1.24g)	VIII (0.34–0.65g)	VII (0.18–0.34g)	VI (0.092–0.18g)	Urban	Rural
Masonry	Unreinforced brick masonry in mud mortar	15	4	0.6	0	35	50
Masonry	Unreinforced brick masonry in cement mortar with reinforced concrete floor/roof slabs	6	1	0.1	0	63	50
Structural concrete	Concrete moment resisting frames designed for gravity loads only	11	2	0.2	0	2	0
Steel	Steel moment resisting frame with brick masonry partitions	1.5	0.2	0	0	0	0

Table 2 Population vulnerability of the UK

	Fatality ratio (%) when subjected to the specified shaking intensity			
	IX (0.65–1.24g)	VIII (0.34–0.65g)	VII (0.18–0.34g)	VI (0.092–0.18g)
In urban areas	0.771	0.167	0.021	0
In rural areas	0.819	0.183	0.024	0

data 3.7), representing population vulnerability due to collapse of buildings of different types (Jaiswal et al. 2009).

The building vulnerability tables are jointed to mortality probabilities caused by building collapse according to building types. Population vulnerability in urban and rural areas are calculated separately according to Eq. (1) to get vulnerability function for each country.

$$\mathrm{FR}_{ij} = \sum_{n=1}^{4} V_{nj} \times R_{nj} \times \mathrm{CR}_{nij} \quad (1)$$

where j refers to the jth nation, and FR_{ij} refers to fatality ratio due to earthquake with intensity i, i = 1, 2, 3, 4. V_{nj} represents mortality probability caused by collapse of n-type building, n = 1, 2, 3, 4. R_{nj} represents population proportion in n-type building, and CR_{nij} refers to collapse probability of n-type building in earthquake with intensity i.

Take UK as an example (Table 2), in urban areas, population mortalities in earthquake with VI, VII, VIII, and IX magnitudes are 0, 0.021, 0.167, and 0.771 %, respectively; while for rural areas, they are 0, 0.024, 0.183, and 0.819 %, respectively.

Due to limited data, we divide the world into 28 regions (UNDP 2010) according to economic development levels and geographic positions, one country is selected to represent the whole region and its population vulnerability is taken as representation of the other countries. If such data are not available in one region, another country with data at the same development level in adjacent region shall be chosen. The following representative countries are selected: Algeria, Argentina, Chile, China, Cyprus, Greece, India, Indonesia, Japan, Macedonia, Mexico, Morocco, Nepal, Pakistan, Peru, Romania, Slovenia, Sweden, Thailand, Turkey, and UK, and the representative countries in 7 regions are replaced by suitable countries in adjacent regions. Accordingly, population vulnerability table for all countries and regions are established.

2.1.2 Seismic Intensity Map

Peak ground acceleration (PGA) (Appendix III, Hazards data 4.1) is widely used to earthquake disaster risk assessment and mapping. Its probability of exceedance is 10 % in 50 years, i.e., once in 475 years. The PGA is converted into intensity map according to Table 3. The grid layer with seismic intensity information is vectorized and spatially overlaid with country unit map, thus the state attributes are generated. There are two kinds of resolution for the grid layer: 0.1° × 0.1° for economic-social wealth (ESW) loss risk assessment and 0.5° × 0.5° for mortality risk assessment.

2.1.3 Mortality Risk

In combination with intensity vector layer with national information and population vulnerability table of each country, and based on intensity information of each vector block patch (0.5° × 0.5°), mortality risk is calculated according to Eq. (2), corresponding to earthquake mortality probability of urban and rural areas of each country under the intensity in vulnerability table.

$$\mathrm{FR}_{j} = \Sigma\mathrm{FR}_{j\mathrm{Urban}} \times \mathrm{UR}_{j} + \Sigma\mathrm{FR}_{j\mathrm{Rural}} \times (1 - \mathrm{UR}_{j}) \quad (2)$$

where FR_j refers to the mortality of vector block in country j; $\mathrm{FR}_{j\mathrm{Urban}}$ refers to the mortality probability in urban area of country j; $\mathrm{FR}_{j\mathrm{Rural}}$ refers to the mortality probability in the

Table 3 Transformation of PGA and intensity (g = 9.81 m/s^2)

Intensity	PGA (g)	PGA (m/s^2)
<VI	<0.05	<0.491
VI	0.05–0.1	0.491–0.981
VII	0.1–0.2	0.981–1.962
VIII	0.2–0.4	1.962–3.924
≥IX	≥0.4	≥3.924

Fig. 2 Expected annual earthquake mortality risk of the world. *1* (0, 10 %] India, Indonesia, Pakistan, Bangladesh, China, Philippines, Burma, Iran, Afghanistan, Uzbekistan, Nepal, and Ethiopia. *2* (10, 35 %] Egypt, Guatemala, Turkey, Kyrgyzstan, Tanzania, Japan, Syria, Bolivia, Tajikistan, Kenya, Mexico, Congo (Democratic Republic of the), Honduras, Uganda, Peru, Chile, Gaza Strip, Georgia, Vietnam, Ecuador, Papua New Guinea, Colombia, Malawi, Nicaragua, United States, Burundi, Algeria, and Moldova. *3* (35, 65 %] Venezuela, Rwanda, Bhutan, Haiti, Kazakhstan, Russia, Laos, El Salvador, Iraq, Azerbaijan, Romania, Costa Rica, Morocco, Turkmenistan, Mozambique, Jordan, Mongolia, Dominican Republic, Albania, Italy, Armenia, Tunisia, Bosnia and Herzegovina, Eritrea, Lebanon, Serbia, Libya, Argentina, Canada, Ukraine, Djibouti, Greece, Cuba, Croatia, and Sudan. *4* (65, 90 %] Somalia, Jamaica, Panama, Gabon, Spain, Zambia, New Zealand, Israel, Germany, United Arab Emirates, Bulgaria, Thailand, Oman, Australia, Switzerland, Austria, Portugal, Macedonia, Palestine, France, Slovenia, Solomon Islands, Iceland, Belgium, Trinidad and Tobago, Congo, Montenegro, Czech Republic, and Slovakia. *5* (90, 100 %] Fiji, Brazil, Cameroon, Cyprus, Central African Republic, Kuwait, Saudi Arabia, Paraguay, Norway, New Caledonia, and Sweden

rural area of country j; UR_j represents the urbanization rate of country j in 2010 from the World Bank.

By converting mortality to raster and overlaying it with world population density map (Appendix III, Exposures data 3.1), the map of mortality risk of the world by earthquake in 0.5° × 0.5° grid could be generated.

2.2 Economic-social Wealth (ESW) Loss Risk

2.2.1 ESW Loss Rate

This study calculates the economic-social wealth loss rate (Appendix III, Exposures data 3.8) using empirical relation between earthquake intensity and economic-social wealth loss. The empirical relation is provided by Munich Reinsurance Company, as shown in Eq. (3) (Badalet al. 2005):

$$\log f(I) = k_0 + k_1 I + k_2 I^2 + k_3 I^3 \tag{3}$$

where I represents the intensity value larger than V, k_0, k_1, k_2, and k_3 are empirical parameters, with two sets of numerical values. When $k_0 = -10.28677$, $k_1 = 2.83516$, $k_2 = -0.24213$, and $k_3 = 0.00793$, the maximum social wealth loss rate can be calculated. While $k_0 = -11.29522$, $k_1 = 2.72825$, $k_2 = -0.20344$, and $k_3 = 0.00581$, the minimum social wealth loss rate can be calculated. The two sets of parameters could describe the inherent uncertainty of social wealth loss caused by different building structures and define the possible range of social wealth loss rate caused by earthquake. This study calculates the social wealth loss rate based on the average of the maximum and minimum values.

2.2.2 ESW Loss Risk

ESW loss value of each grid of the world is calculated by a combination of world social wealth data, the loss rate of each grid and earthquake intensity.

3 Results

3.1 Mortality Risk

The world earthquake mortality risk map in 0.5° × 0.5° grid is produced based on spatial analysis, using the world PGA data, building vulnerability data, mortality probability data caused by building collapse, and population density data. The spatial pattern of world earthquake mortality risk is similar to that of tectonic fault zone; however, the pattern is affected by the exposure.

The expected annual mortality risk of earthquake of the world at national level is derived and ranked (Fig. 2) by adding mortality risks of all grids confined by country boundary and then dividing the sum by the return period (475 years).

Fig. 3 Expected annul ESW loss risk of earthquake of the world. *1* (0, 10 %] Japan, United States, China, Turkey, Italy, Mexico, Chile, Canada, Indonesia, Venezuela, Iran, Philippines, Colombia, Greece, Peru, India, Puerto Rico, Germany, and United Arab Emirates. *2* (10, 35 %] New Zealand, Russia, Spain, Pakistan, Israel, Australia, Kazakhstan, Costa Rica, United Kingdom, Romania, Guatemala, Switzerland, Uzbekistan, Ecuador, Azerbaijan, Belgium, Egypt, Croatia, Malaysia, El Salvador, Oman, Bulgaria, Gaza Strip, Thailand, Syria, Trinidad and Tobago, Hungary, Afghanistan, the Netherlands, Algeria, Brazil, Slovakia, Serbia, Saudi Arabia, Kuwait, Lebanon, Cyprus, Nepal, and Panama. *3* (35, 65 %] Bolivia, Kyrgyzstan, Slovenia, Poland, Tajikistan, Georgia, Honduras, Singapore, Iceland, Jordan, Norway, Czech Republic, Jamaica, Bosnia and Herzegovina, South Africa, Nicaragua, Tunisia, South Korea, Turkmenistan, Libya, Papua New Guinea, Albania, Armenia, Ukraine, Morocco, Kenya, Macedonia, Sweden, Montenegro, Nigeria, Vietnam, Ethiopia, Luxembourg, Yemen, Denmark, Ireland, Uganda, Moldova, Tanzania, Liechtenstein, San Marino, Finland, Antigua and Barbuda, Haiti, Laos, Mongolia, Andorra, Ghana, Rwanda, Angola, Gabon, Congo (Democratic Republic of the), Fiji, Baker Island, Bhutan, and Malawi. *4* (65, 90 %] Cameroon, Malta, South Sudan, Zambia, Grenada, Solomon Islands, North Korea, Mozambique, Djibouti, Palestine, Qatar, Sudan, Belize, Eritrea, Dominica, Lithuania, Uruguay, Samoa, Burundi, Swaziland, Bahrain, Sri Lanka, Timor-Leste, Guinea, Paraguay, Belarus, The Republic of Côte d'Ivoire, Saint Lucia, Congo, Cambodia, Saint Vincent and the Grenadines, Latvia, Equatorial Guinea, Saint Kitts and Nevis, Chad, Togo, Estonia, Central African Republic, Zimbabwe, Benin, Barbados, Sierra Leone, Botswana, Namibia, Federated States of Micronesia, Tonga, Kiribati. *5* (90, 100 %] Guyana, Madagascar, Suriname, Senegal, Somalia, Niger, Lesotho, Liberia, Mauritania, Mali, Bahamas, Western Sahara, Guinea-Bissau, Palau, Comoros, Marshall Islands, Maldives, Gambia, and Niue

The top 1 % country with the highest expected annual earthquake mortality risk is India, and the 10 % countries are India, Indonesia, Pakistan, Bangladesh, China, Philippines, Burma, Iran, Afghanistan, Uzbekistan, Nepal, and Ethiopia.

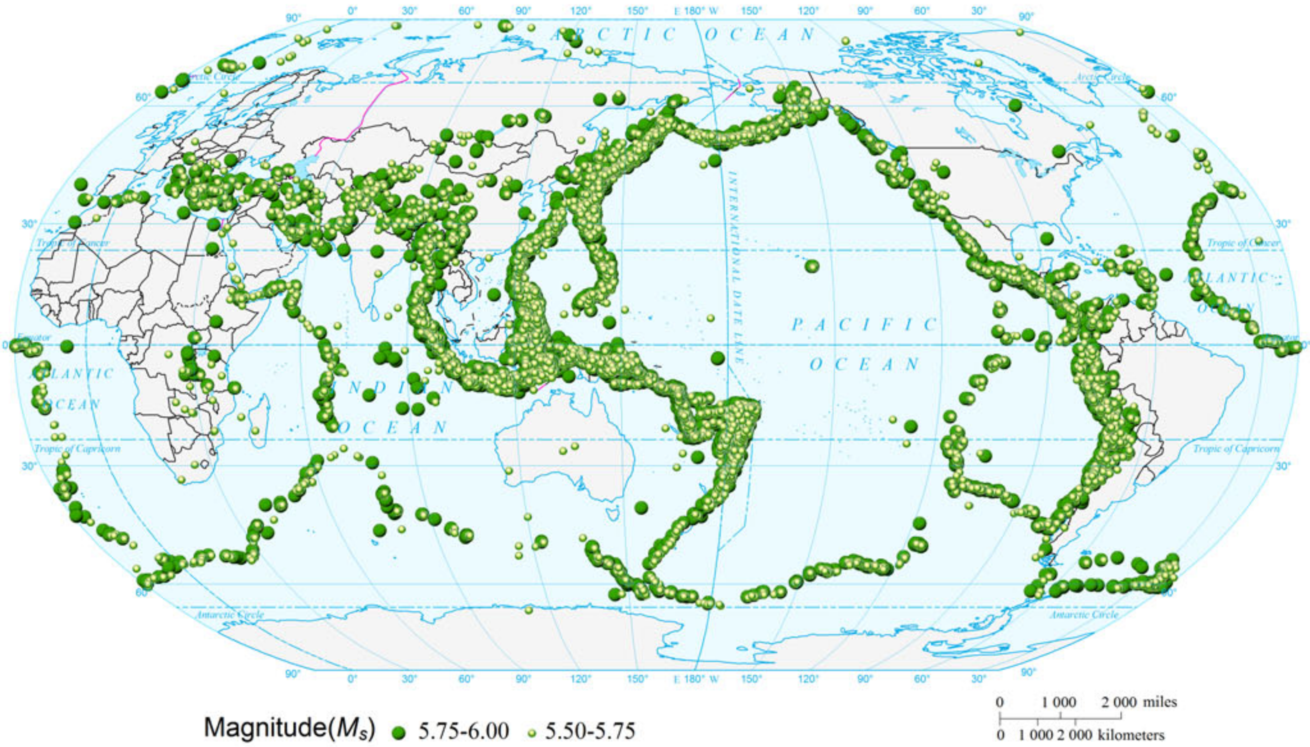
3.2 ESW Loss Risk

The earthquake ESW loss risk of the world in $0.1° \times 0.1°$ grid is acquired based on spatial analysis. Replacing GDP with the calculated world social wealth data as the exposure of economic and combining global PGA data and the calculated social wealth loss rate, ESW loss risk is assessed. The spatial pattern of world ESW loss risk is similar to that of tectonic fault zone; however, the pattern is also affected by the exposure.

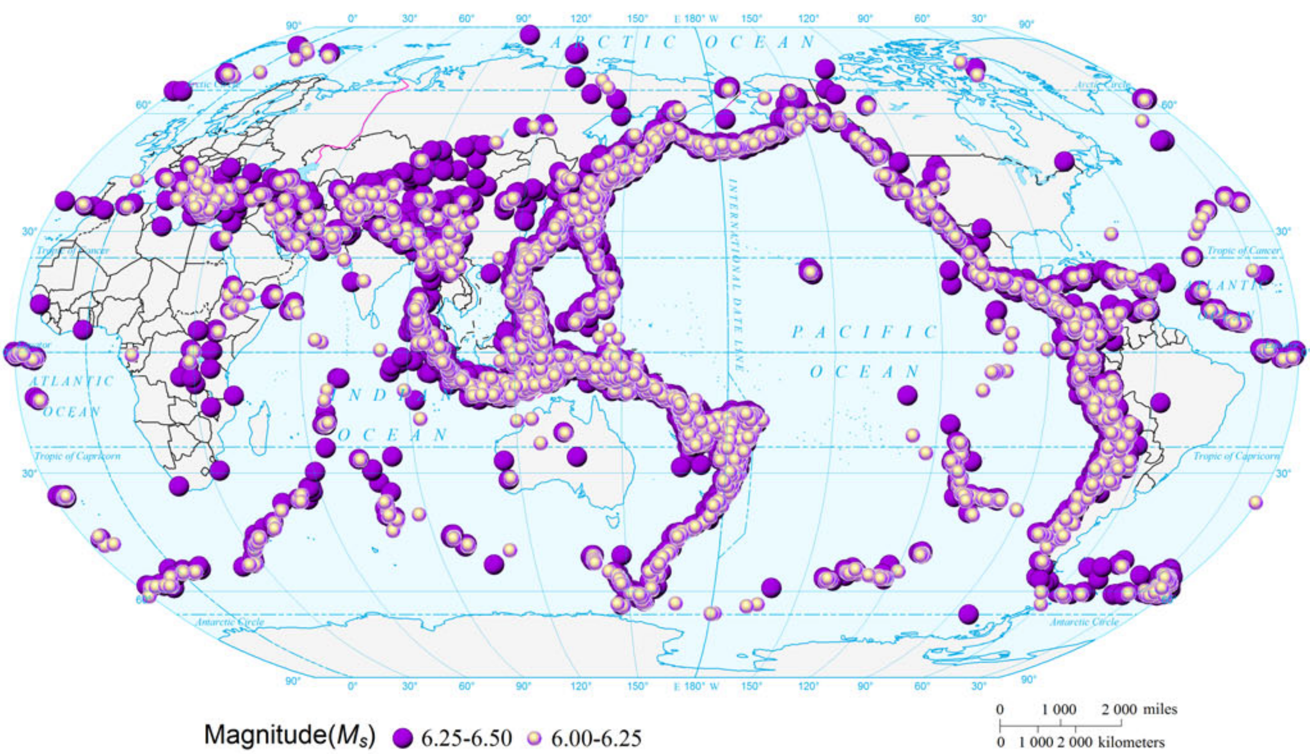
By zonal statistics of the expected risk result, the world expected annual ESW loss risk of earthquake of the world at national level is derived and ranked (Fig. 3) by adding ESW loss risks of all grids confined by country boundary and then dividing the sum by the recurrence interval (475 years). The top 1 % countries with the highest expected annual ESW risk of earthquake are Japan and United States, and the 10 % countries are Japan, United States, China, Turkey, Italy, Mexico, Chile, Canada, Indonesia, Venezuela, Iran, Philippines, Colombia, Greece, Peru, India, Puerto Rico, Germany and United Arab Emirates.

4 Maps

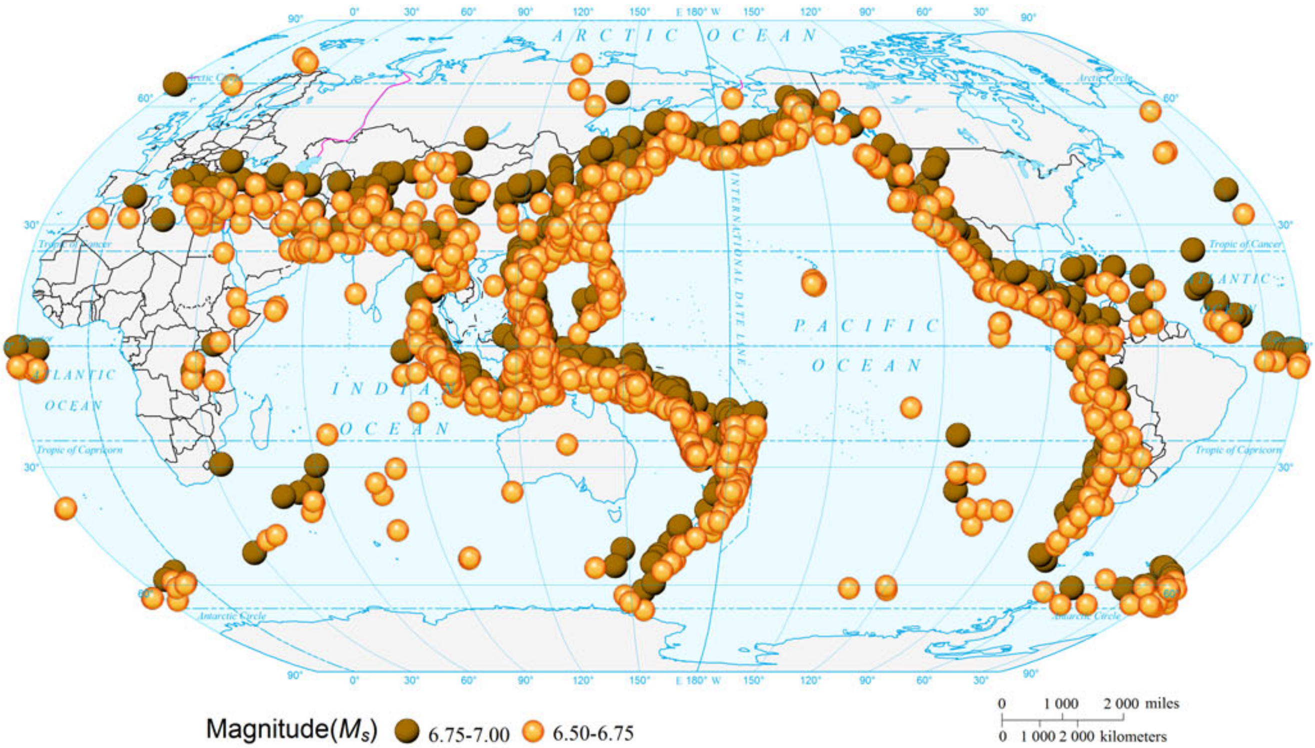
Historical Event Locations of Global Earthquake (1900-2009, 5.50≤M_s<6.00)



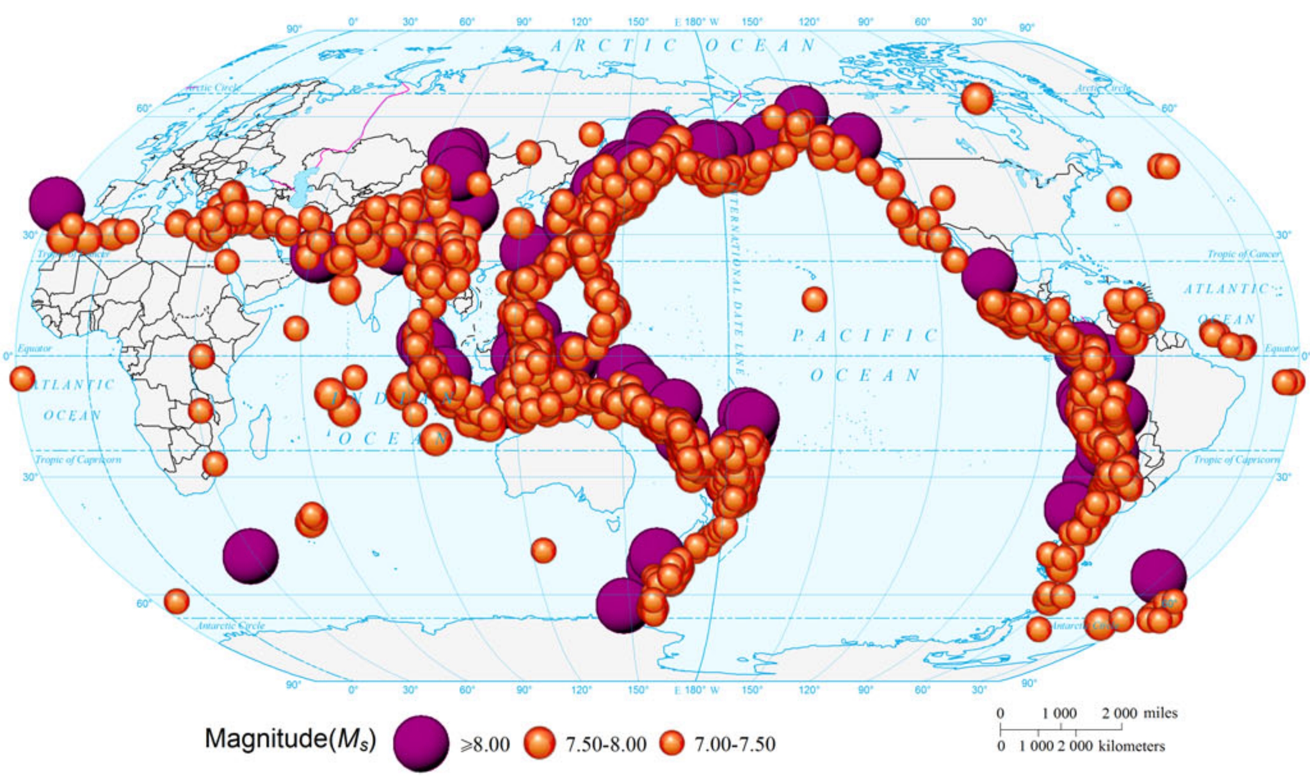
Historical Event Locations of Global Earthquake (1900-2009, 6.00≤M_s<6.50)

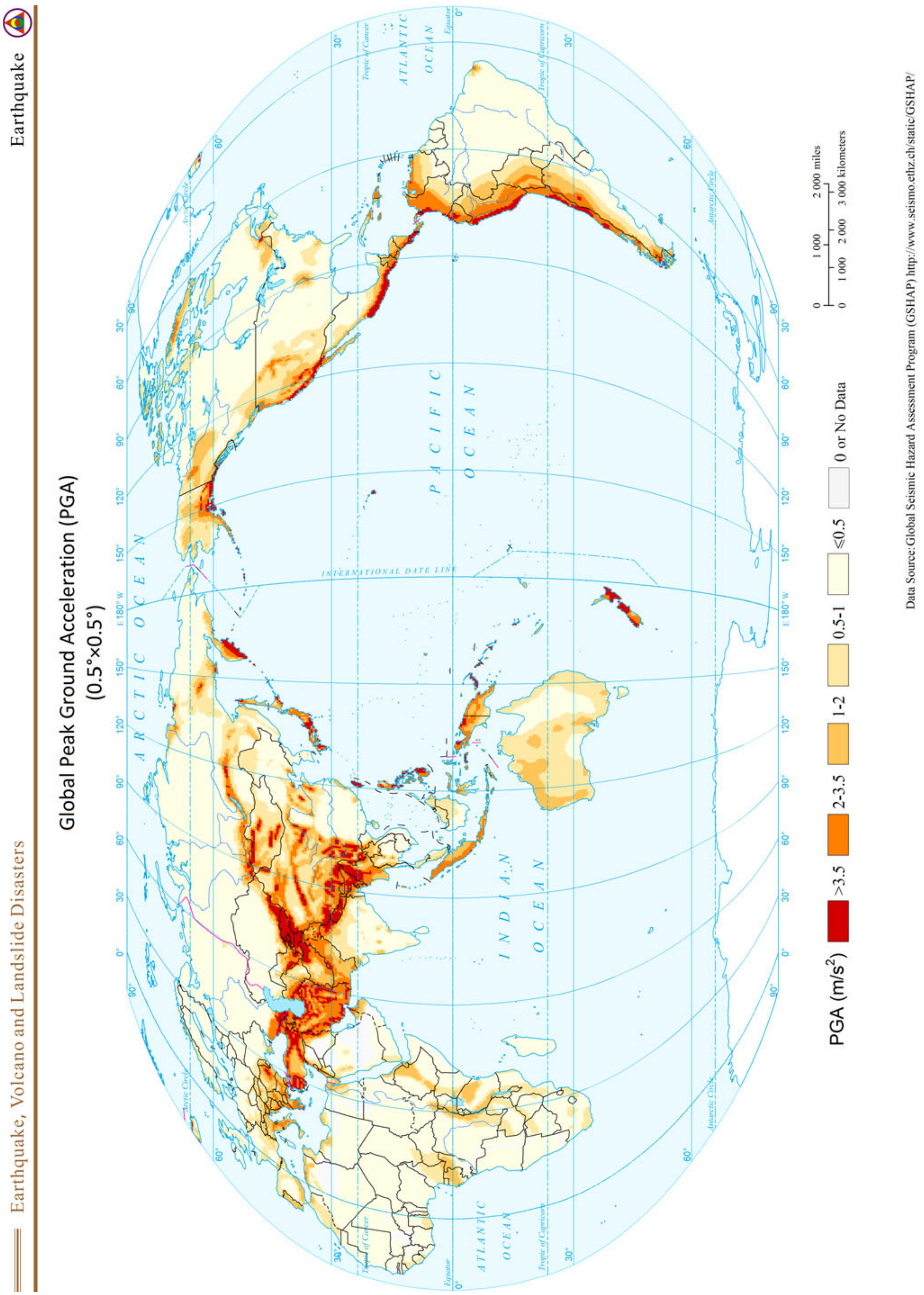


Historical Event Locations of Global Earthquake (1900-2009, $6.50 \leqslant M_S < 7.00$)

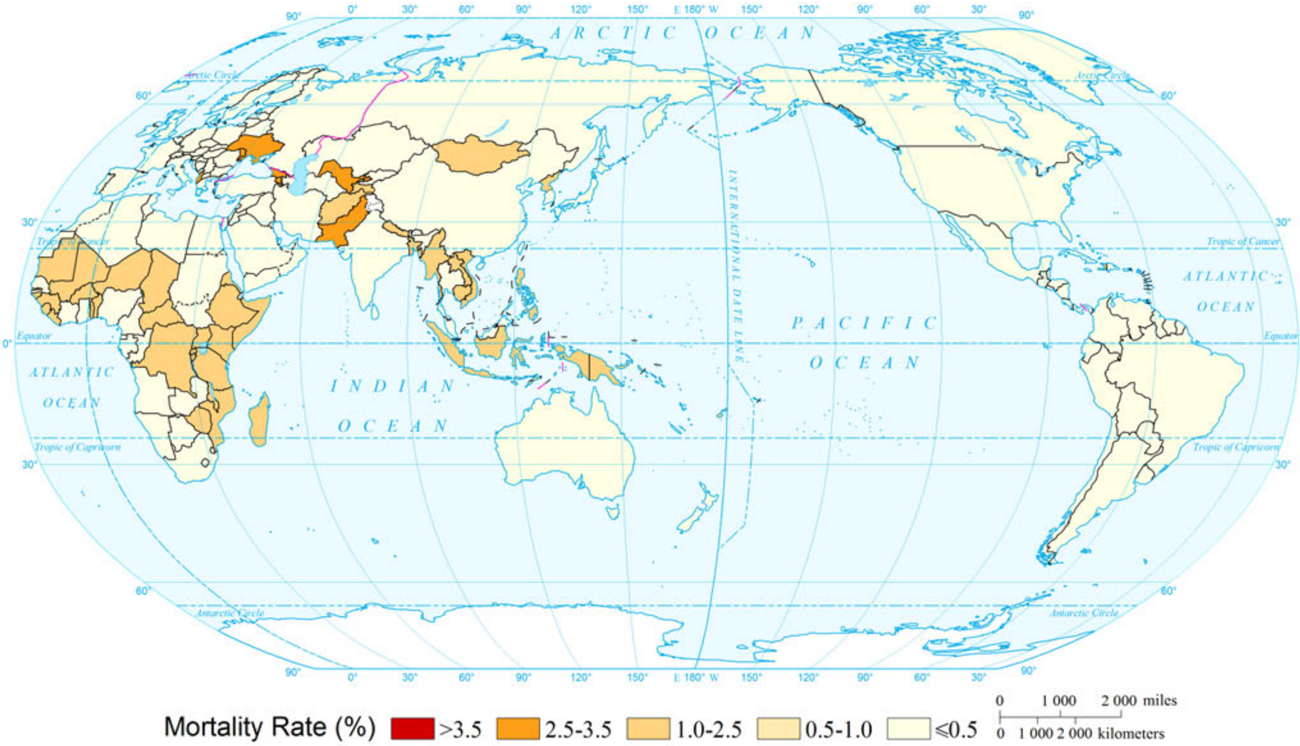


Historical Event Locations of Global Earthquake (1900-2009, $M_S \geqslant 7.00$)

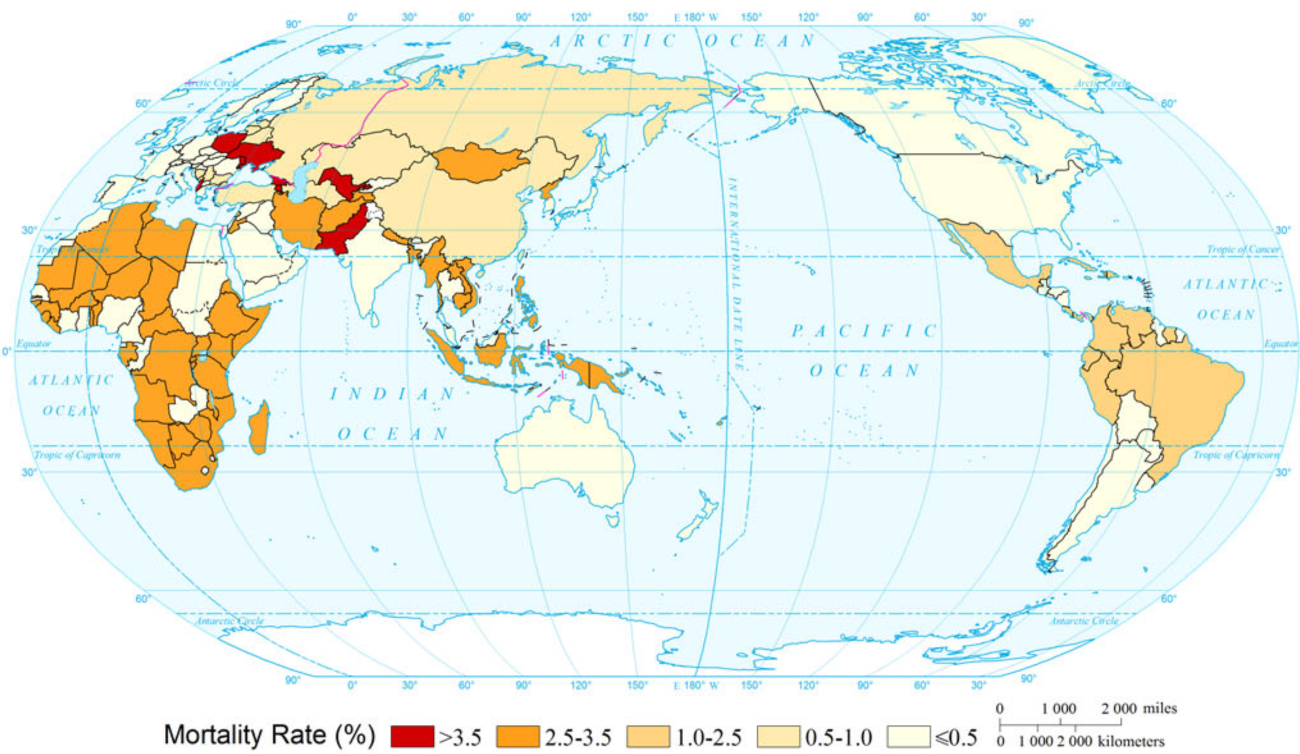



Earthquake, Volcano and Landslide Disasters
Earthquake
Global Peak Ground Acceleration (PGA)
(0.5°×0.5°)
ARCTIC OCEAN
ATLANTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
INTERNATIONAL DATE LINE
Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
Antarctic Circle
PGA (m/s²)
>3.5
2-3.5
1-2
0.5-1
≤0.5
0 or No Data
0 1 000 2 000 miles
0 1 000 2 000 3 000 kilometers
Data Source: Global Seismic Hazard Assessment Program (GSHAP) http://www.seismo.ethz.ch/static/GSHAP/

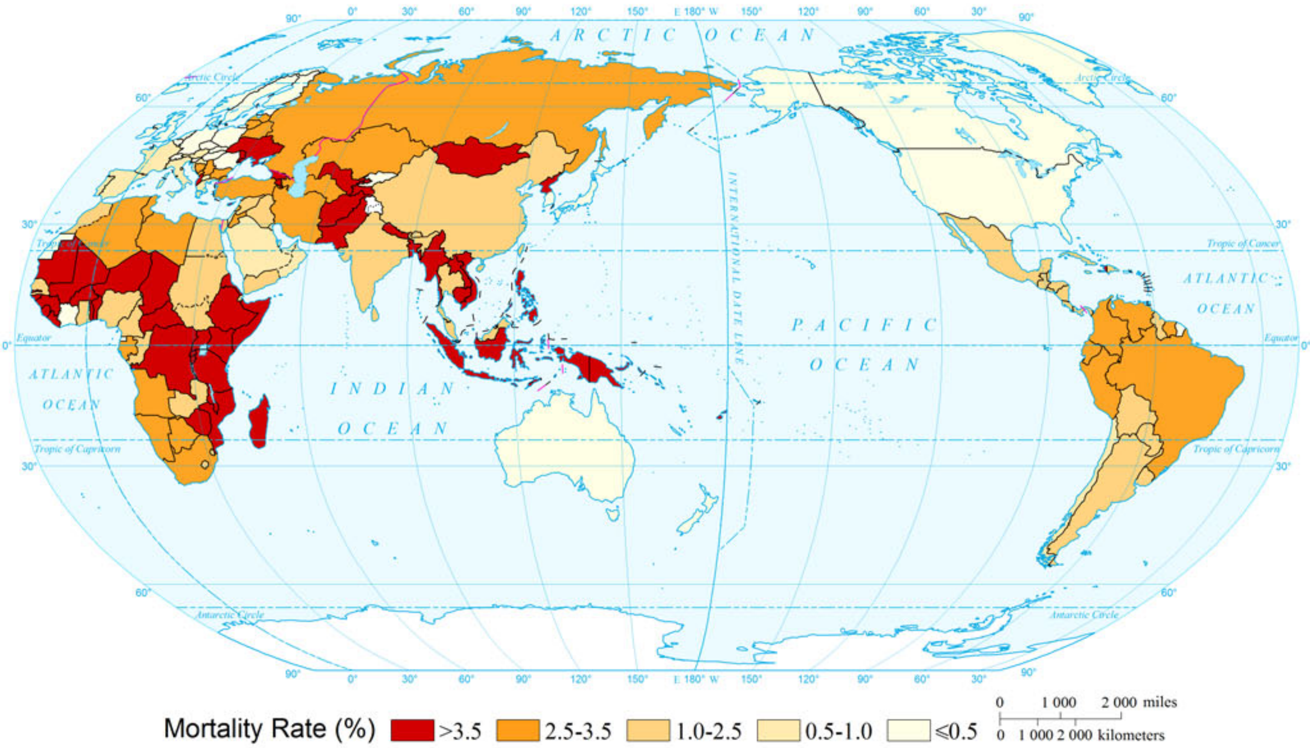
Mortality Rate of Earthquake Disaster (Intensity =VI) of the World



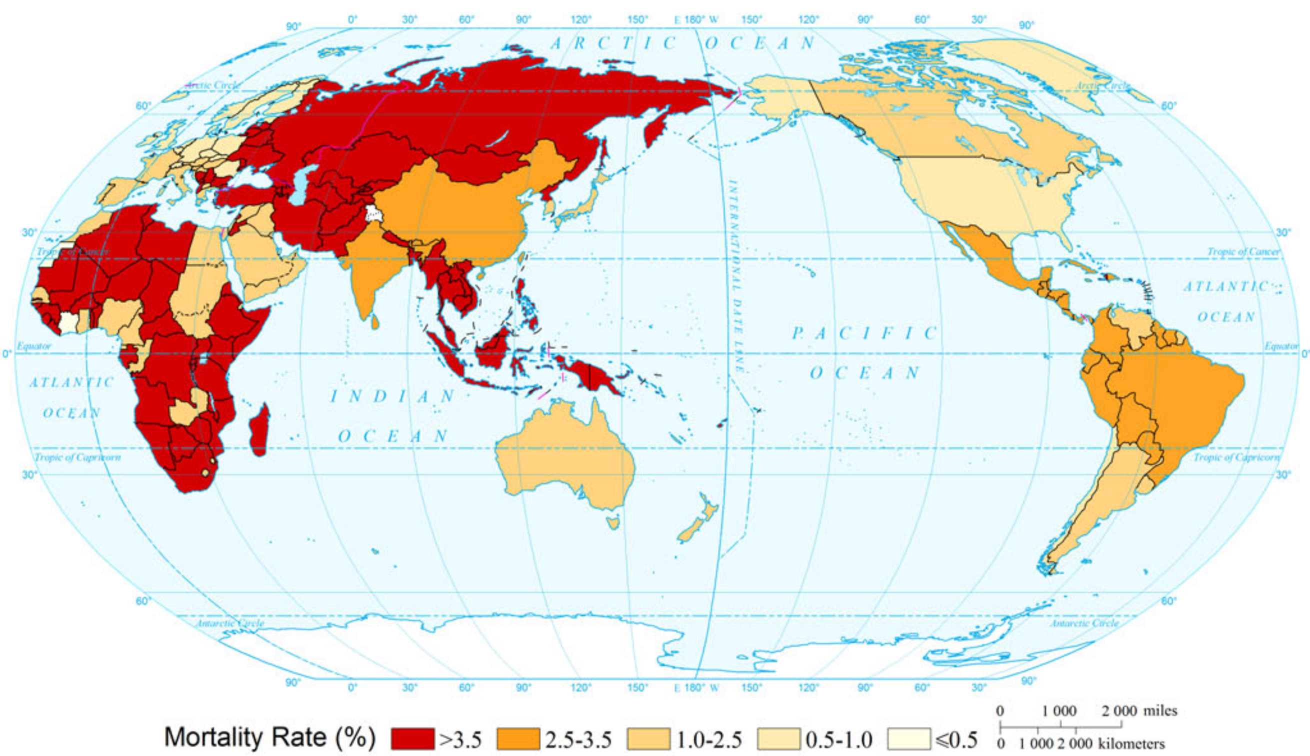
Mortality Rate of Earthquake Disaster (Intensity =VII) of the World

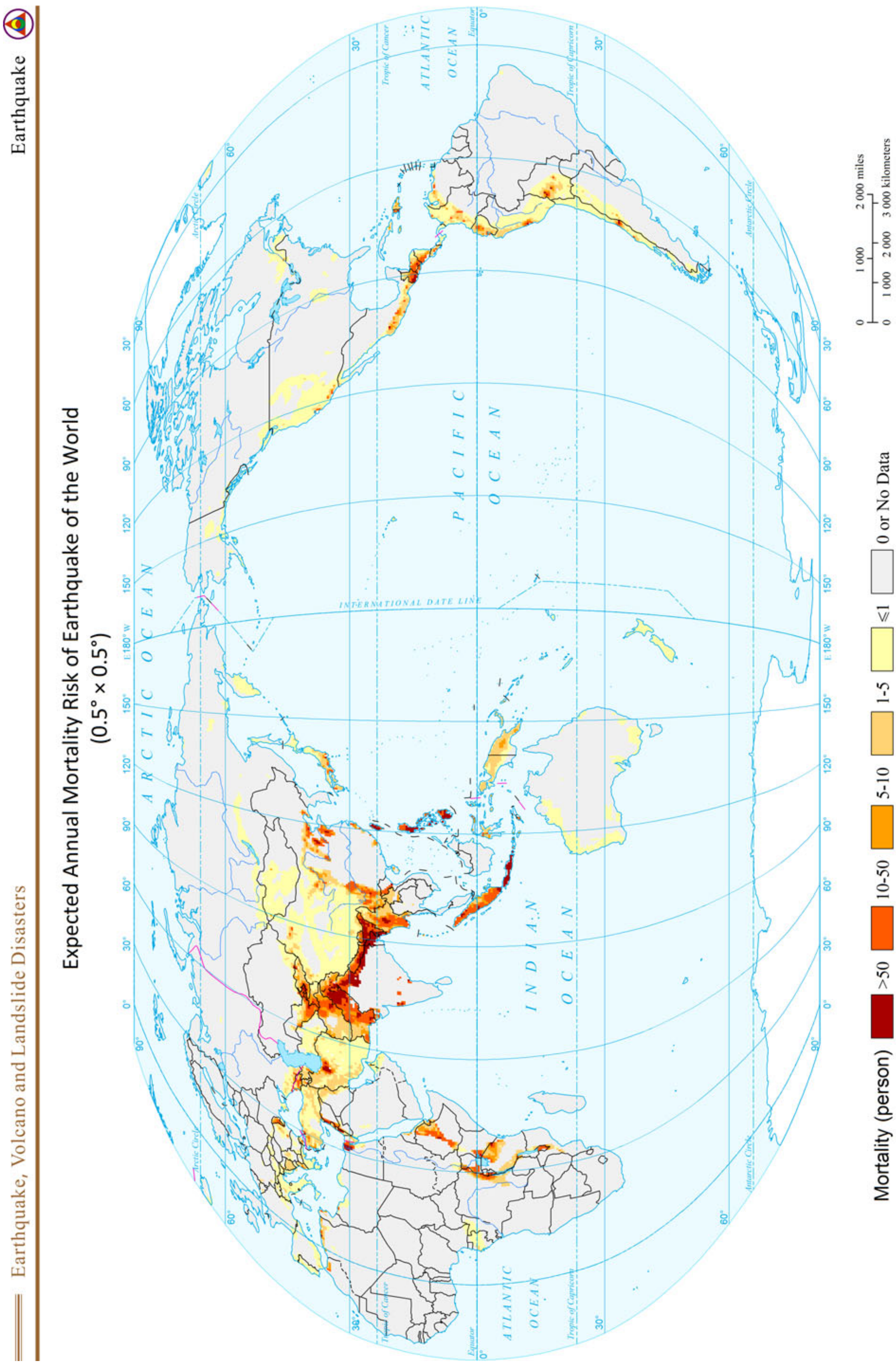


Mortality Rate of Earthquake Disaster (Intensity=VIII) of the World

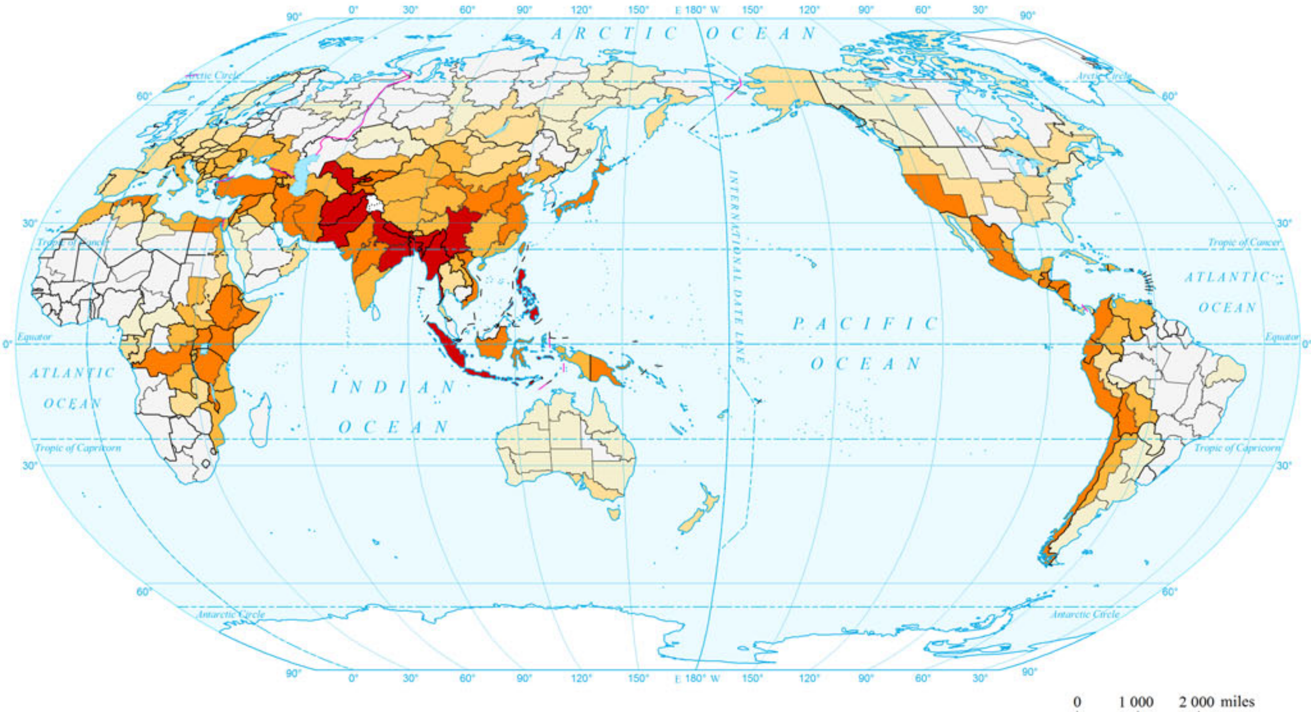


Mortality Rate of Earthquake Disaster (Intensity≥IX) of the World



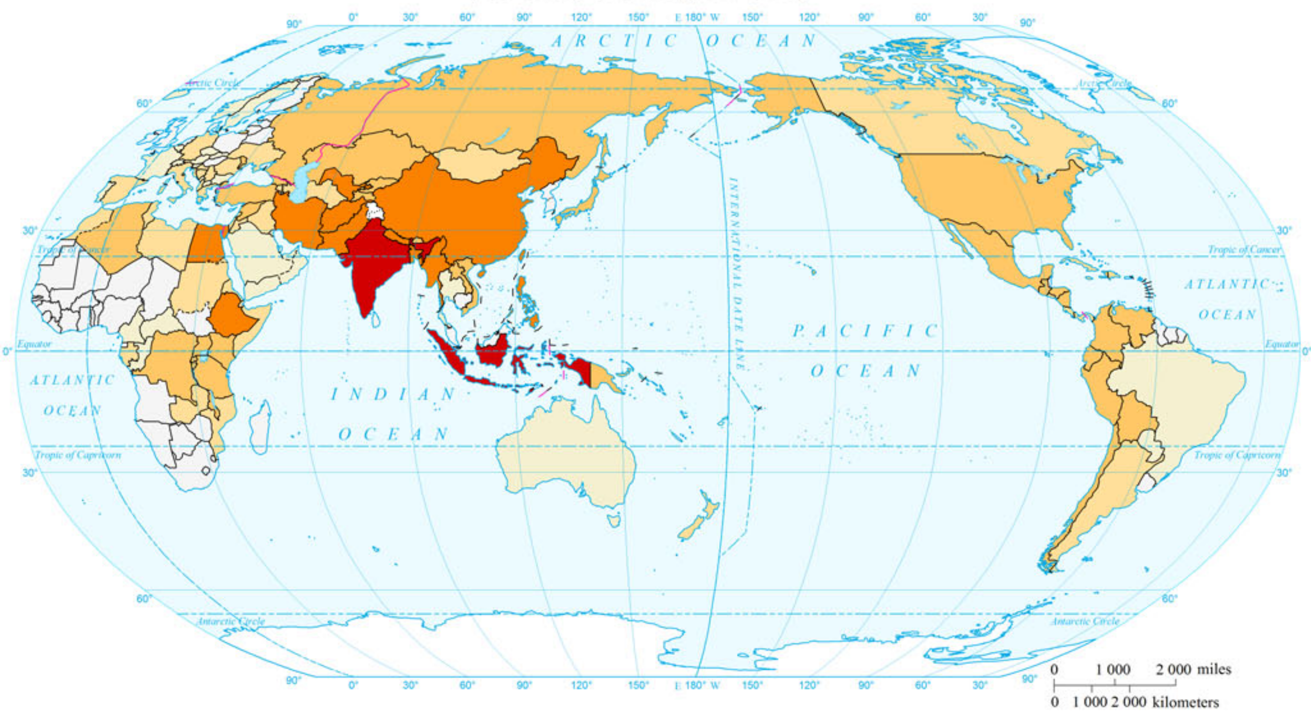

Earthquake, Volcano and Landslide Disasters
Earthquake
Expected Annual Mortality Risk of Earthquake of the World
(0.5° × 0.5°)
ARCTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
ATLANTIC OCEAN
INTERNATIONAL DATE LINE
Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
Antarctic Circle
Mortality (person)
>50
10-50
5-10
1-5
≤1
0 or No Data
0 1 000 2 000 miles
0 1 000 2 000 3 000 kilometers

Expected Annual Mortality Risk of Earthquake of the World
(Comparable-geographic Unit)

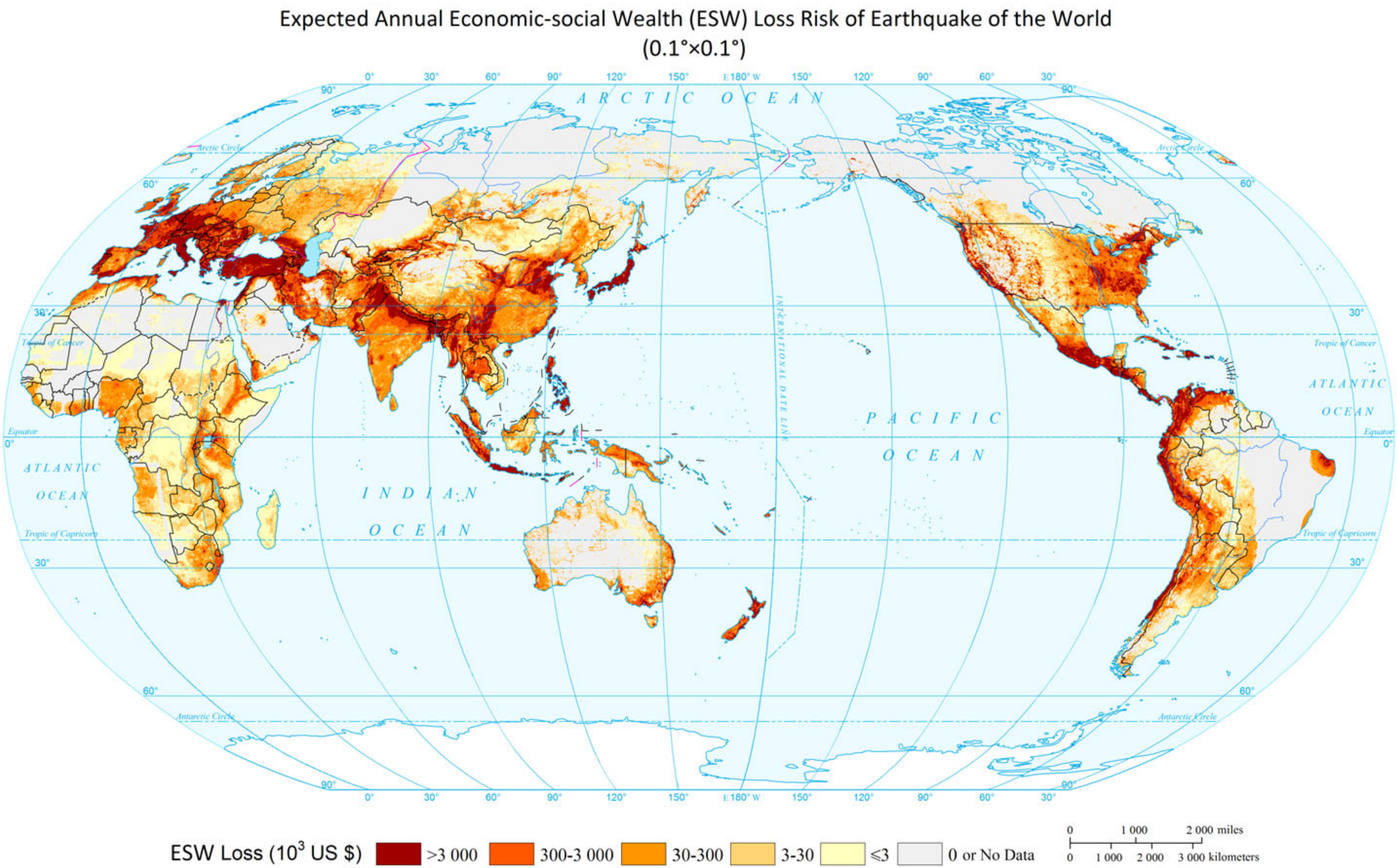


Mortality (person) >2 000 200-2 000 20-200 1-20 ≤1 0 or No Data

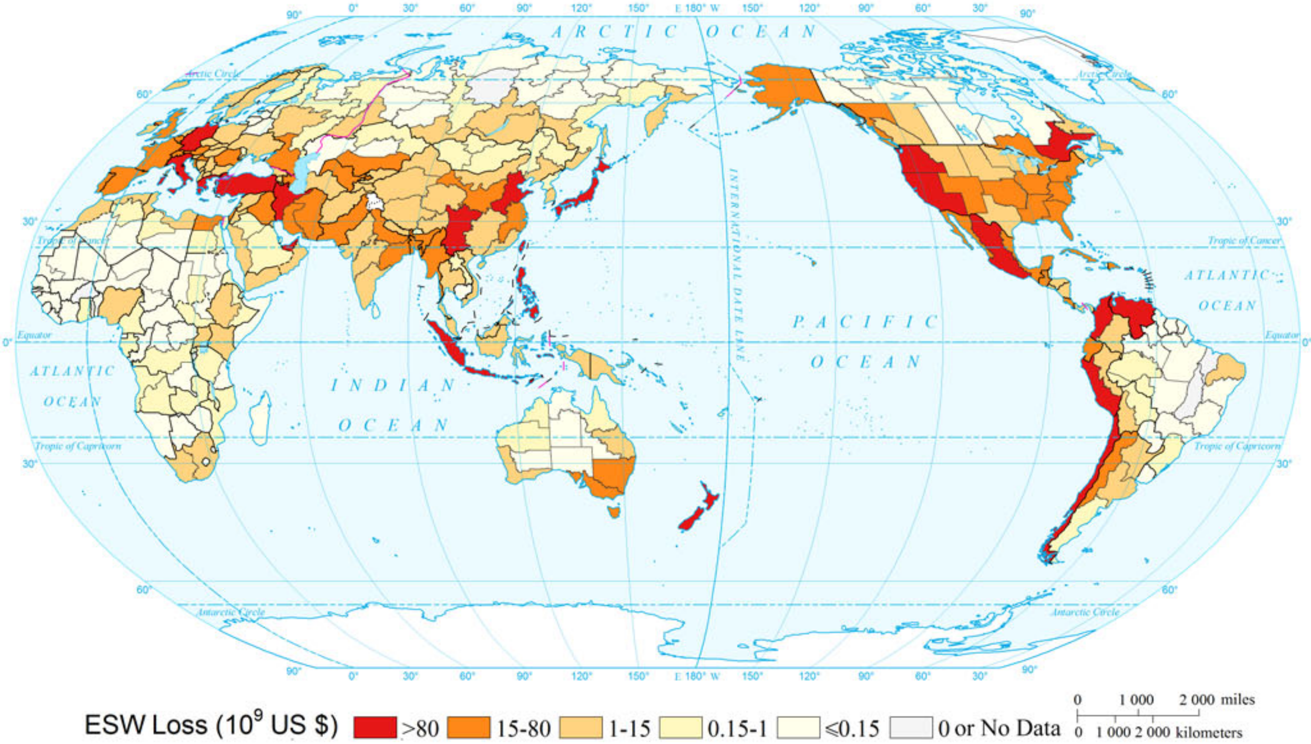
Expected Annual Mortality Risk of Earthquake of the World
(Country and Region Unit)



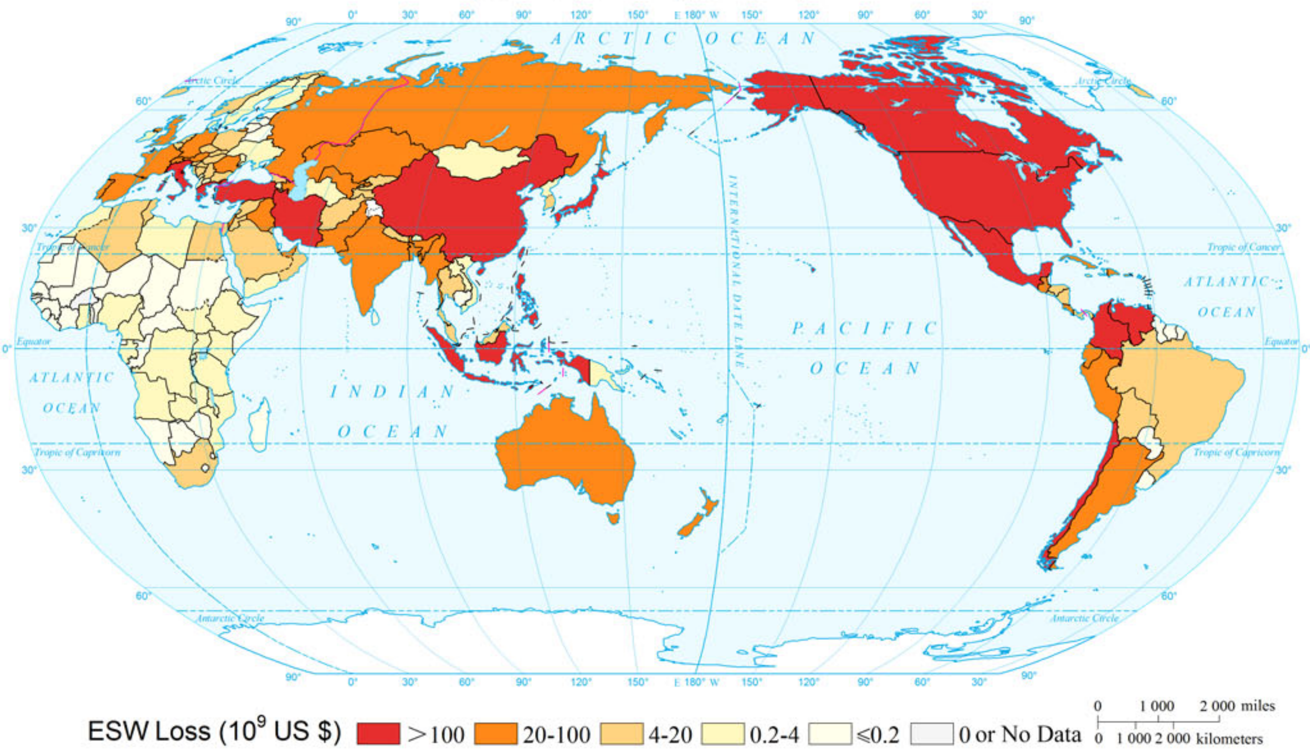
Mortality (person) >10 000 1 000-10 000 100-1 000 10-100 ≤10 0 or No Data


Expected Annual Economic-social Wealth (ESW) Loss Risk of Earthquake of the World
(0.1°×0.1°)
ARCTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
ATLANTIC OCEAN
INTERNATIONAL DATE LINE
Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
Antarctic Circle
ESW Loss (10^3 US $)
>3 000
300-3 000
30-300
3-30
≤3
0 or No Data
0 1 000 2 000 miles
0 1 000 2 000 3 000 kilometers

Expected Annual Ecnocmic-social Wealth (ESW) Loss Risk of Earthquake of the World
(Comparable-geographic Unit)



Expected Annual Economic-social Wealth (ESW) Loss Risk of Earthquake of the World
(Country and Region Unit)



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