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Unified Scaling Law for Earthquakes: Seismic hazard and risk assessment for Himalayas, Lake Baikal, and Central China regions

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Method

The results of the global and regional analyses (Keilis-Borok et al., 1989; Kossobokov & Mazhkenov, 1994; Kossobokov & Nekrasova, 2003; 2005; 2007; Nekrasova & Kossobokov 2002; 2003; 2006; Nekrasova, 2008) imply that the recurrence of earthquakes at a seismically prone site, for a wide range of magnitudes M and sizes $L \in (L_1, L_2)$, can be described as Unified Scaling Law for Earthquakes (USLE) by the following formula:

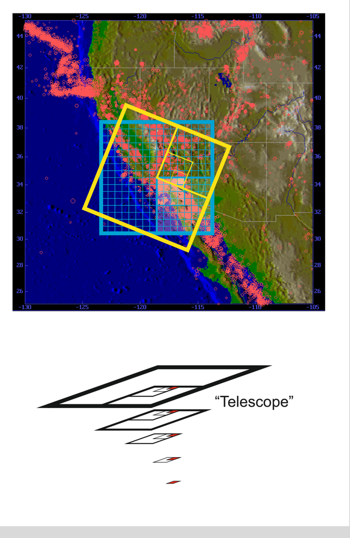
$$N(M, L) = 10^A \times 10^{B \times (5-M)} \times L^C$$

where $L \times L$ is a square embedding seismic locus and A, B, C are constants.

A catalogue of earthquakes is used as initial input data source. A space-time-magnitude volume, $S \times T \times M$ is considered, where S is the territory, T is time interval from T_0 to T_1, and M is the magnitude range above M_0; the events with magnitude $m \geq M_0$ are reasonably complete in the catalogue since T_0. The input data are processed as follows (Fig. 1):

1. The magnitude range M is subdivided into q adjacent intervals of length ΔM –
$M_j = \{m : M_0 + (j-1)\,\Delta M \leq m < M_0 + j\,\Delta M\}$, $j = 1, 2, \ldots, q$.

2. The entire area S is subdivided into a hierarchy of h levels. The 0-level corresponds to the entire S imbedded in a square of side length L_0 (a square of side length L here is a set $\{(x, y) : x_0 \leq x < x_0 + L;\ y_0 \leq y < y_0 + L\}$). In the two successive levels i and $i+1$ ($i = 0, 1, \ldots, h-1$) of hierarchy each square of side length L_i is split into the four equal squares of side length $L_{i+1} = L_i/2$. A square at the level i of this hierarchy can be denoted as $w_i(e)$ for any point e inside it and, at the same time, as Q_i^r where r is the index number of this square between 1 and 4^i.



3. Using the earthquake catalog, for each one out of the q magnitude ranges and for each one out of the h levels of hierarchy, the following number N_i is computed

$$N_i = [\textstyle\sum (n(Q_i^r))^2] / N_i \qquad (3)$$

where summation extends over all areas $\{Q_i^r\}$ at the i-th level of hierarchy; $n(Q_i^r)$ is the number of events from a magnitude range M_j in an area Q_i^r of linear size L_i; N_i is the total number of events from a magnitude range M_j.

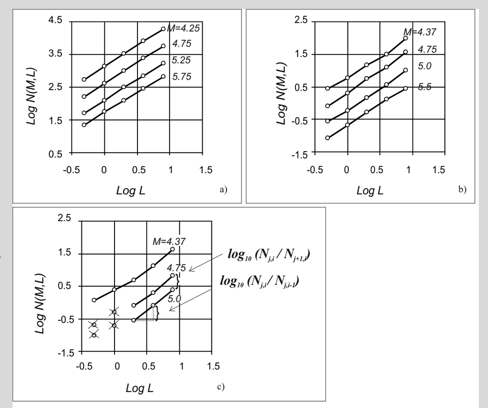
It should be mentioned that this estimate of fractal dimension suggested in (Kossobokov and Mazhkenov 1988; 1994), although originally very close in motivation to estimation of the Hausdorff capacity dimension D_0 (Mandelbrot 1982), in essence, corresponds to the correlation dimension D_2 (Atmanspacher et al. 1988).

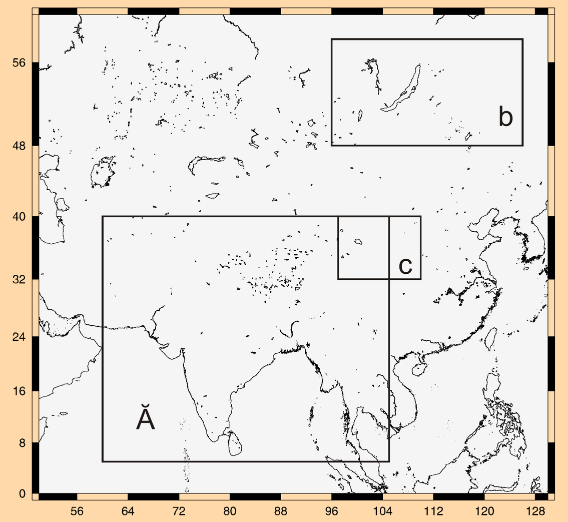
Usually, N_i are normalized in time to 1 year and in space to an area of 1 degree of the Earth meridian in length.

4. Estimates of A, B, and C in (2) are derived from the set of linear algebraic equations $\log_{10} N_{ij} = A - B(M_j - M_0) + C\log L_i$ by the least squares method. Unlike many other recent applications (e.g., Bak et al. 2002) the method makes heuristic adjustments for heterogeneity of seismic distribution, as well as for consistency of the real data statistics in different magnitude ranges. Specifically, the equations that correspond to evidently incomplete samples of data due to extremely low recurrence rates of higher magnitude earthquakes in an area are excluded from computations. For this purpose a heuristic limitation requiring $\log_{10}(N_{ij}/N_{ij+1}) > const$ on transfer from the magnitude range M_j to M_{j+1} (where const is a free parameter of the SCE algorithm, usually set to 2) is used. Similar limitation - $\log_{10}(N_{ij}/N_{i-1j}) > const$ - is introduced for the transfer from the $(i-1)$-th to i-th level of spatial hierarchy.

5. In addition to the original prototype algorithm (Kossobokov and Mazhkenov 1988), the steps 1-4 are applied many (usually 100) times with randomized box counting setups at each seismically active location (Nekrasova and Kossobokov 2002). The resulting series of multiple estimates of the three coefficients are used to determine the final average values of A, B, and C along with their standard errors σ_A, σ_B, and σ_C.

The graphs of typical counts of N_{ij} for a region : a model sample of "epicenters" on the classical Koch's curve and the real one for the area of Los-Angeles mega-agglomeration are well constrained, while a sample from the US Geological Survey and National Earthquake Information Center, USGS/NEIC, Global Hypocenters Data Base System catalogue (GHDB, 1989) for an area of Tokyo may exemplify possible complications and the heuristic adjustments for heterogeneity of seismic distribution of the SCE algorithm.





The Unified Scaling Law for Earthquakes (USLE), that generalizes the Gutenberg–Richter recurrence relation, has evident implications since any estimate of seismic hazard depends on the size of the territory that is used for investigation, averaging, and extrapolation into the future. Therefore, the hazard may differ dramatically when scaled down to the proportion of the area of interest (e.g. territory occupied by a city) from the enveloping area of investigation. In fact, given the observed patterns of distributed seismic activity the results of multi-scale analysis embedded in USLE approach demonstrate that traditional estimations of seismic hazard and risks for cities and urban agglomerations are usually underestimated.

Moreover, the USLE approach provides a significant improvement when compared to the results of probabilistic seismic hazard analysis, e.g. the maps resulted from the Global Seismic Hazard Assessment Project (GSHAP). We apply the USLE approach to evaluating seismic hazard and risks to population of the three territories of different size representing a sub-continental and two different regional scales of analysis, i.e. the Himalayas and surroundings, Lake Baikal, and Central China regions.

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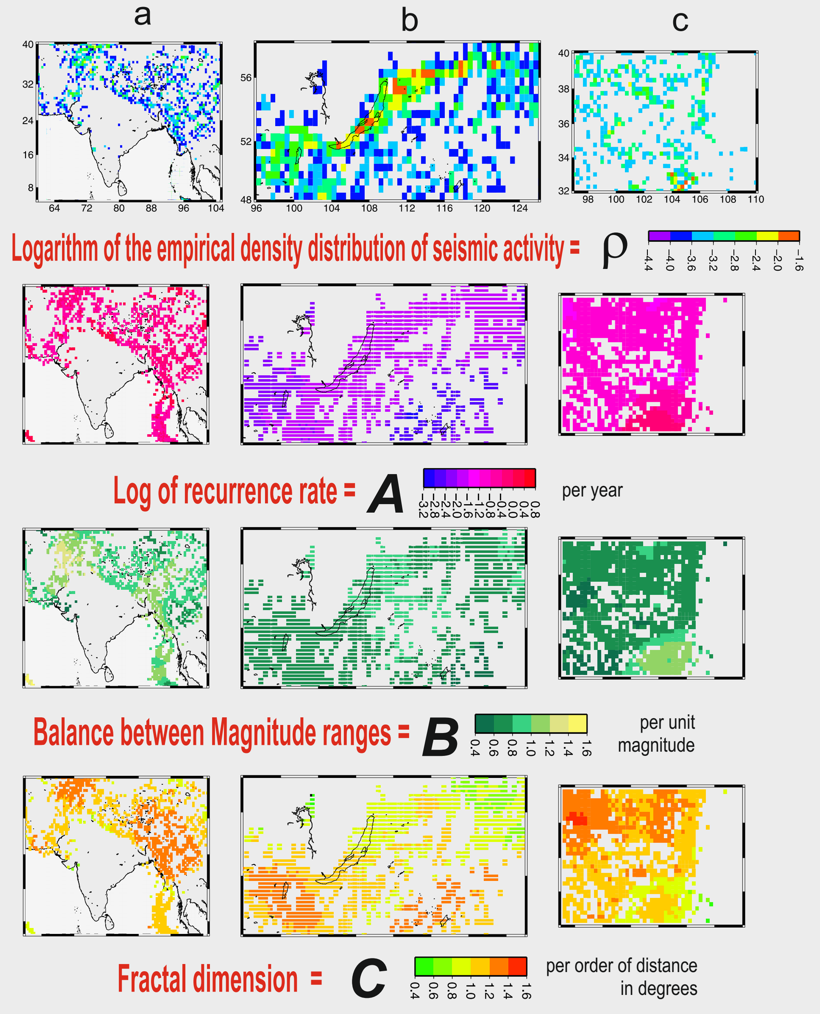
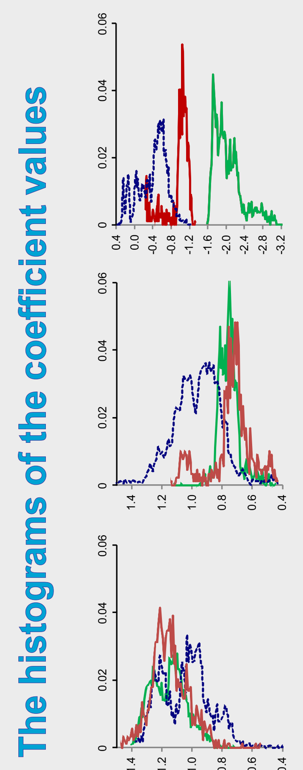
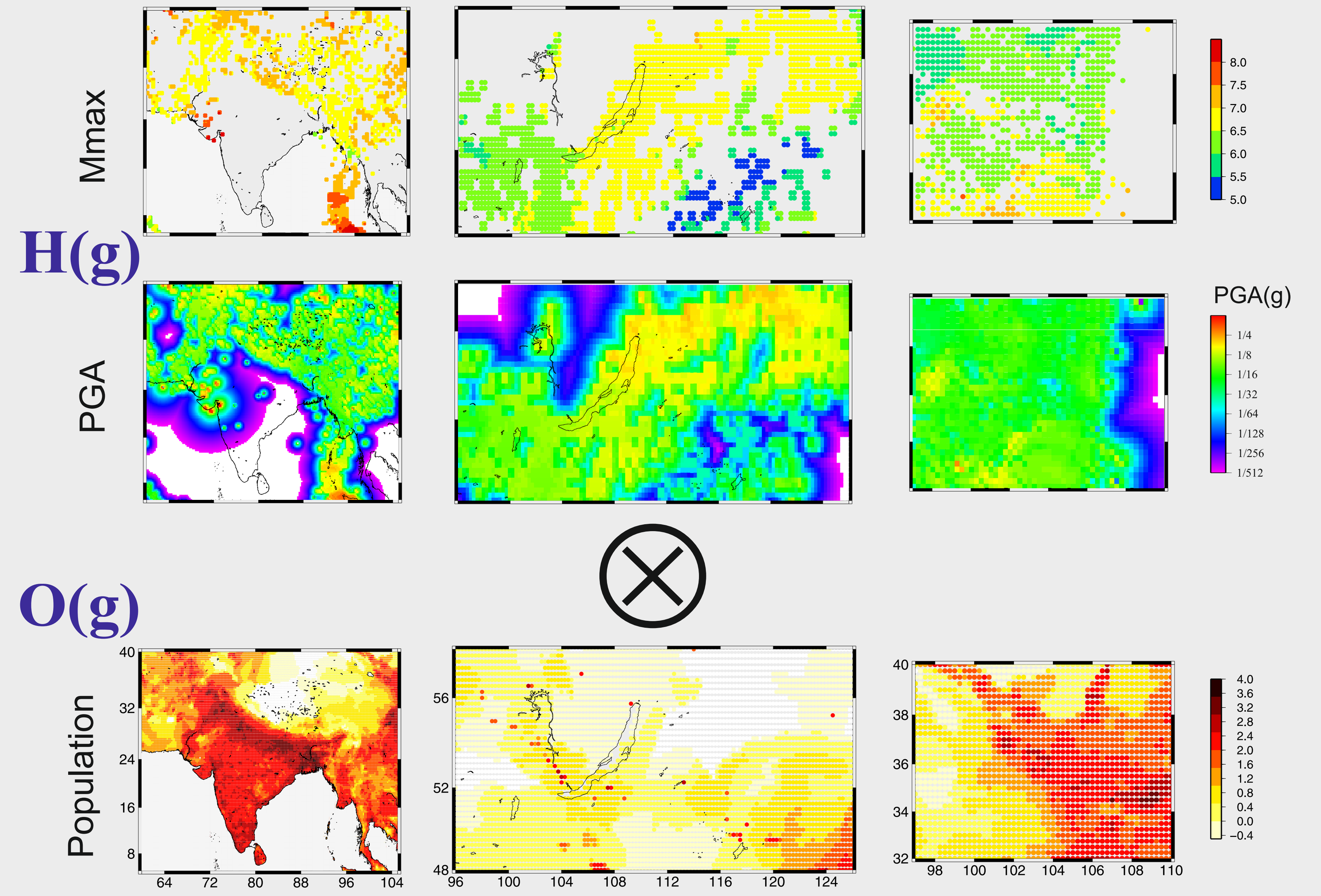
USLE coefficients estimation

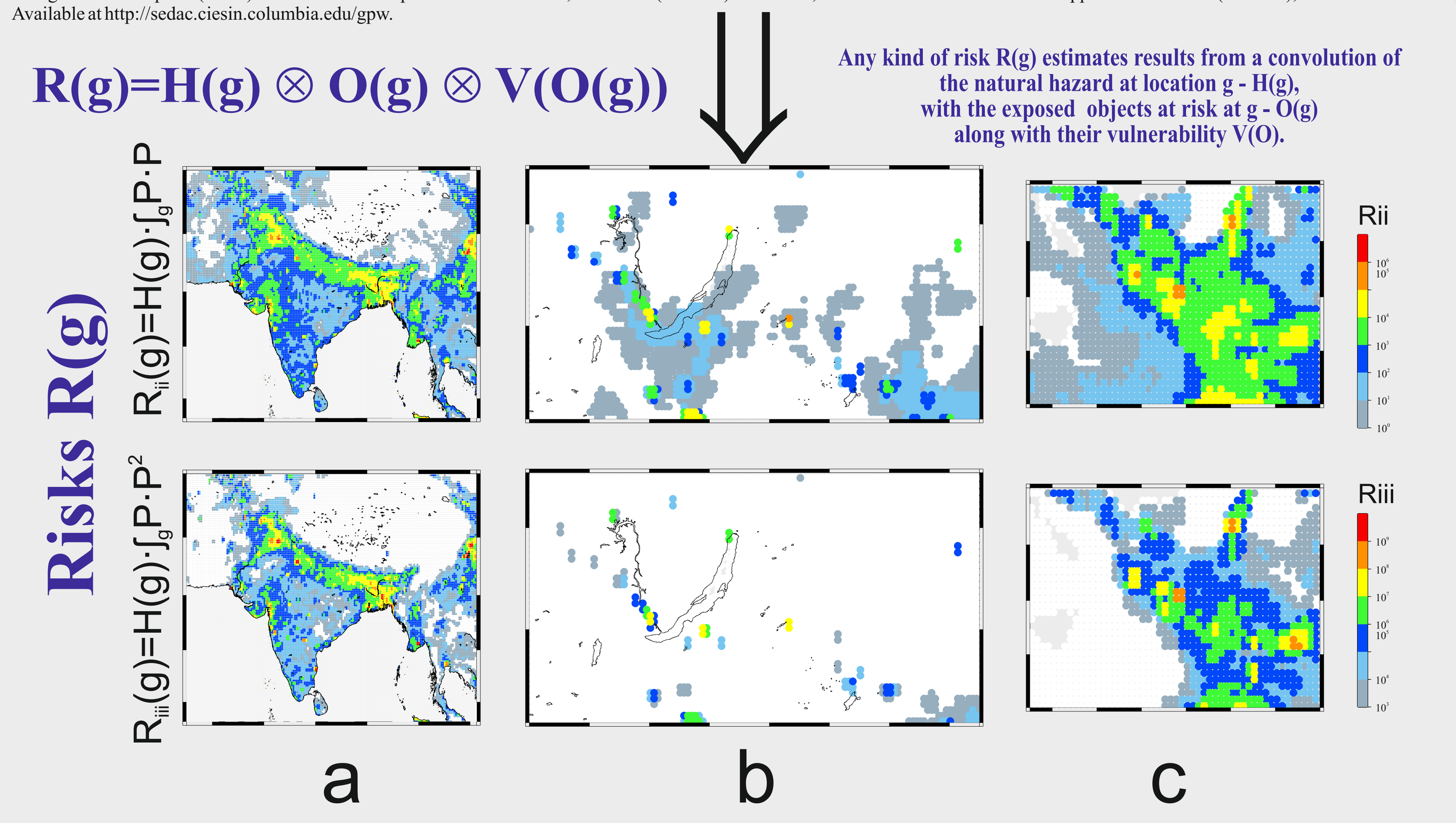




Seismic hazard and risk estimation



The population density distribution based on GPWv3 estimate for 2010 by Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). 2005. Gridded Population of the World, Version 3 (GPWv3). Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw.



The USLE coefficients were used for estimation and mapping the expected maximum magnitude M_{max} with a 10% chance of exceedence in 50 years. Specifically, for each 0.5°×0.5° cell at seismic location on a regional map we calculate the expected numbers of events from magnitude ranges M_j in 50 years, i.e. $N_{50}(M_j, 0.5°) = 50 \times N(M_j, 0.5°)$, and then find the maximum magnitude, M_{max}, with the expected number $N_{50}(M_{max}, 0.5°) \geq 10\%$. Naturally, these are the estimates of traditional maximum magnitude with 10% chance of exceedence in 50 years.

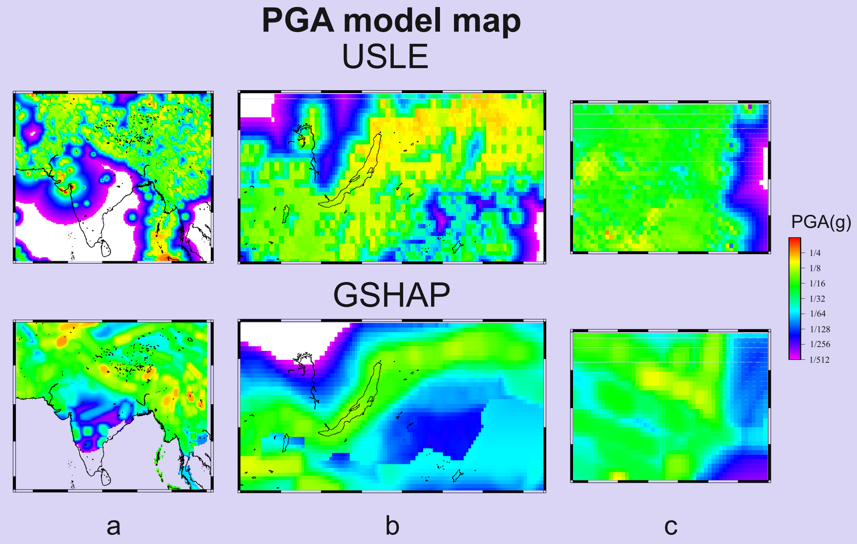
For each grid point we apply the empirical formula for acceleration produced by a source of M_{max} as inspired from (Parvez et al. 2001) –

$$\mathrm{Acc}(M_{max}, D) = \mathrm{const} \times g \times D^{-1.5} \times exp(M_{max} - 5),$$

where D is the source-receiver distance on a 0.25°×0.25° grid, const = 6, g = 9.81 m/s^2 is the gravity constant, and $exp(x)$ is the natural exponent of x. The maximum of acceleration values computed at a grid point is assigned to it. We have opted the minimum and maximum distances of 10 km and 500 km, respectively.

Verification

Rigorous and objective testing of seismic hazard assessments against the real seismic activiy must become the necessary precondition for any responsible seismic risk estimation.



The Global Seismic Hazard Assessment Program (GSHAP) was initiated in 1992 and approved as a demonstration project under the International Decade for Natural Disaster Reduction declared by the United Nations Organization (UN/IDNDR). The GSHAP was completed in 1999 and the probabilistic seismic hazard assessment maps (Giardini et al. 1999; Shedlock et al. 2000) displaying global distribution of maximum PGA with 10% chance of exceedence in 50 years in the 0.1°×0.1° mesh were published (the archive containing the GSHAP PGA numerical evaluations for the whole world is in open access at http://www.seismo2009.ethz.ch/GSHAP/gshpub.zip).

The maps obtained by GSHAP differ from those based on USLE dramatically. At a glance the USLE based maps appear to be more selective and avoid some of the errors of GSHAP like the locations of the 2001 Bhuj and 2004 Sumatra-Andoman great earthquakes on the sub-continental scale map of Himalayas and surroundings.

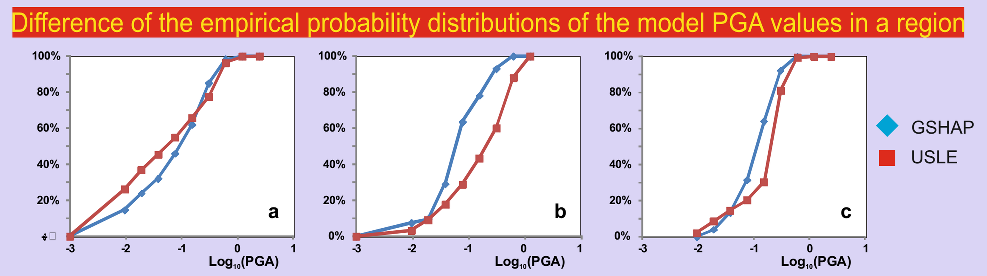
The number of earthquakes with the estimated PGA values at epicenter exceeding the value on the model map

Model map	GSHAP				USLE based			
Himalayas and surroundings								
PGA ratio	any	>2	>4	>8	any	>2	>4	>8
M = 5	4666	86	39	17	4746	36	23	18
M = 6	702	57	21	8	706	5	2	0
M = 7	121	33	14	5	121	5	2	0
Lake Baikal region								
PGA ratio	any	>2	>4	>8	any	>2	>4	>8
M = 5	176	7	3	0	176	4	1	1
M = 6	42	5	3	0	42	3	1	1
M = 7	7	3	2	0	7	2	0	0
Central China region								
PGA ratio	any	>2	>4	>8	any	>2	>4	>8
M = 5	158	5	4	1	158	2	1	0
M = 6	37	5	4	1	37	2	1	0
M = 7	7	4	4	1	7	2	1	0

Let us check both approaches at the locations of real earthquakes of magnitude 5 or larger with hypocenters above 70 km as reported in the USGS/NEIC Global Hypocenters Data Base System for the time period from 1900 to the present

The USLE model outscore GSHAP in identifying correctly the sites of moderate, strong, and significant earthquakes. Specifically, the number of unacceptable errors, when PGA value on a map at epicenter of real earthquake is by factor 2 or greater less than attributed to this earthquake, is several times larger for the GSHAP map than for the USLE one (e.g., 11.4, 1.7, and 2.5 times for strong earthquakes in Himalayas and surroundings, Lake Baikal, and Central China region, respectively).

Difference of the empirical probability distributions of the model PGA values in a region



For both models the percentage of unacceptable errors increase with magnitude: from 2% to 27% for GSHAP and from 1% to 4% for USLE in Himalayas, from 4% to 43% for GSHAP and from 2% to 29% for USLE in Baikal, and from 3% to 57% for GSHAP and from 1% to 29% for USLE in Central China.