Application of Time-independent and Time-dependent Occurrence Models on the Seismic Hazard Estimations in the Marmara region, Turkey

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Introduction

We calculate the probability of occurrence of characteristic earthquakes, Mw > 6.5, for 26 individual fault sources in the Marmara region, Turkey (Figure 1) in the next 50 year period (starting from January 1, 2014) using time-independent and time-dependent earthquake forecasting models. The time-dependency is introduced by 1) the Brownian Passage Time (BPT) probability model based on a simple physical model of the earthquake cycle and 2) the fusion of the BPT renewal model with a physical model that considers the earthquake probability perturbation for interacting faults by static Coulomb stress changes (BPT+ΔCFF). We treat the uncertainties in the slip rate, depth of the seismogenic layer and aperiodicity of the statistical distribution associated to each examined fault source, by a Monte Carlo technique. The Monte Carlo samples for all these parameters are drawn 100 times from a normal (or Gaussian) random distribution within their uncertainty limits.

For a comparison among the results of the probabilities obtained from the three different models we consider the 16th, 50th and 84th percentiles of the Monte Carlo distribution, taking into account the uncertainties in the fault parameters.

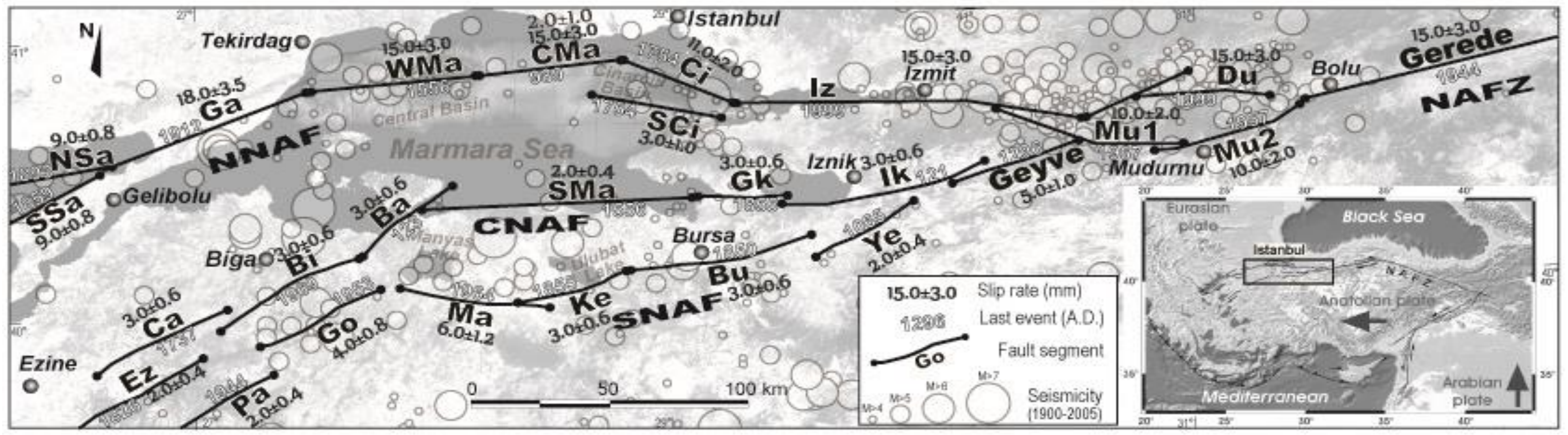

Figure 1. Fault segmentation model and seismic activity with M>4.0 from1/1/1900 to 31/12/2005 in the Marmara region. The slip rates are also shown. Panel on the right show some segments of Main Marmara Fault, to the south of Istanbul.

Data

Information on the strong characteristic earthquakes (Mw>6.5) in the Marmara region is provided in Table 1 with the parameters adopted for our calcolations.

Only earthquakes that break all or most of the area of a fault segment are considered in the computation of total seismic moment release, and as the characteristic earthquakes of the specific segment.

The dimensions of the aftershock zones of recent strong earthquakes, the seismically released strain as well as the seismic moment of the characteristic earthquake in each fault segment were used for the calculation of the mean return periods, in agreement with Field et al. (BSSA, 1999):

$$T_r = \frac{10^{(1.5M+9.05)}}{\mu \cdot V \cdot L \cdot W}$$

Where M is the maximum expected magnitude for each segment. The slip rates (V) assigned to each fault segment are based both on published geodetic (Ergintav et al., GRL 2014) and geologic data. The area of each rupture is computed by magnitude-area Ellsworth relationship (WGCEP, 2003):

M= 4.2 + log (A)

#	Fault name	M_w	Last Event (AD)	L (km)	H (km) 50th percent.	W (km) 50th percent.	Slip Rate (mm/yr)	T-elapsed (yr)	Recurrence Time (yr) ±1σ	Poisson 50 years Prob. ±1σ	BPT 50 years Prob. ±1σ	ΔCFF (MPA) ±1σ	BPT +ΔCFF 50 years Prob. ±1σ
1	Izmit (SS)	7.4±0.1	17/08/1999	158	10±1.2	10±1.1	15.0±3.0	15	181±36	4.30±2.15%	2.70±2.25%	1.98±2.18	20.50±9.4%
2	Cinarcik (SS)	7.0±0.2	1766	44	14±3.0	14±3.1	11.0±2.0	248	155±35	5.40±2.70%	54.50±9.60%	0.54±0.16	54.65±9.65%
3	South Cinarcik (N)	6.8±0.2	02/09/1754	48	7±1.6	8±1.7	3.0±1.0	260	455±153	3.41±1.71%	13.93±4.87%	3.21±0.47	21.25±5.15%
4	C Marmara (SS)	7.1±0.2	989	49	16±3.4	16±3.4	2.0±1.0	1025	968±455	2.44±1.22%	11.08±3.72%	2.28±0.88	11.98±3.92%
5	W Marmara (SS)	7.2±0.2	10/05/1556	61	16±2.7	16±2.8	15.0±3.0	458	147±38	6.40±3.20%	56.65±11.95%	0.39±0.08	56.65±11.95%
6	Ganos (SS)	7.4±0.1	09/08/1912	74	21±2.0	21±2.0	18.0±3.5	102	152±38	6.00±3.00%	44.05±7.55%	0.02±0.01	44.15±7.55%
7	North Saros (SS)	7.1±0.2	09/02/1893	46	17±3.8	18±4.1	9.0±0.8	121	216±52	4.50±2.25%	28.85±6.55%	0.17±0.05	28.05±6.35%
8	South Saros (SS)	7.1±0.2	21/08/1859	45	17±3.7	17±3.9	9.0±0.8	155	211±49	4.40±2.20%	35.40±6.30%	4.90±1.08	43.85±7.85%
9	Mudurnu (SS)	7.2±0.1	22/07/1967	70	14±1.4	14±1.4	10.0±2.0	47	215±38	3.20±1.60%	7.99±5.32%	4.91±1.09	38.40±5.90%
10	Abant (SS)	7.2±0.1	26/05/1957	55	18±1.8	18±1.8	10.0±2.0	57	216±41	3.60±1.80%	11.12±6.28%	7.77±1.73	41.80±8.90%
11	Duzce (SS)	7.1±0.1	12/11/1999	42	18±2.0	19±2.1	15.0±3.0	15	130±25	5.10±2.55%	11.19±6.21%	0.00±0.00	11.19±6.21%
12	Gerede (SS)	7.4±0.1	01/02/1944	165	10±1.0	10±1.0	15.0±3.0	70	182±37	4.30±2.15%	22.20±8.30%	0.00±0.00	22.20±8.30%
13	Geyve (SS)	7.0±0.2	01/06/1296	49	13±3.0	13±3.0	5.0±1.0	718	349±100	3.70±1.85%	28.20±5.90%	0.70±0.11	28.20±6.00%
14	Iznik (SS)	7.4±0.2	01/01/121	74	21±4.5	22±4.6	3.0±0.6	1893	919±243	1.41±0.71%	12.01±3.30%	1.95±0.67	11.97±3.34%
15	Yenisehir (SS)	6.8±0.2	01/09/1065	40	10±1.8	10±1.9	2.0±0.4	949	700±160	1.54±0.77%	15.20±3.60%	0.31±0.17	15.25±3.75%
16	Gemlik (N)	6.8±0.2	11/04/1855	30	10±1.9	13±2.5	3.0±0.6	159	442±113	2.64±1.32%	6.58±3.62%	0.06±0.02	6.30±3.60%
17	Bursa (SS)	6.8±0.2	19/04/1850	67	6±1.3	6±1.3	3.0±0.6	164	452±116	2.56±1.28%	6.78±4.02%	0.50±0.28	9.05±3.85%
18	S Marmara (N)	7.1±0.2	10/05/1556	96	6±1.3	8±1.7	2.0±0.4	458	1009±282	1.35±0.68%	4.28±2.22%	1.27±0.51	6.91±1.80%
19	Kemalpasa (SS)	7.0±0.2	28/02/1855	41	15±3.7	15±3.8	3.0±0.6	159	580±181	2.54±1.27%	3.14±2.69%	0.96±0.10	6.63±3.47%
20	Manyas (N)	6.9±0.1	10/06/1964	55	9±0.3	12±0.4	6.0±1.2	50	296±58	2.80±1.40%	2.31±1.99%	0.08±0.04	2.57±2.15%
21	Bandirma (N)	7.0±0.2	10/11/123	41	12±2.5	16±3.2	3.0±0.6	1891	583±149	2.04±1.02%	19.75±5.55%	0.42±0.30	19.70±5.60%
22	Gonen (SS)	7.1±0.1	18/03/1953	50	15±1.8	16±1.9	4.0±0.8	61	480±114	2.30±1.15%	0.41±0.407%	0.17±0.03	0.67±0.66%
23	Biga (SS)	7.0±0.2	03/03/1969	57	11±2.3	11±2.5	3.0±0.6	45	580±167	2.32±1.16%	0.03±0.03%	0.00±0.00	0.03±0.03%
24	Pazarkoy (N)	6.8±0.1	06/10/1944	54	6±0.6	7±0.8	2.0±0.4	70	680±156	1.59±0.80%	0.06±0.06%	0.00±0.00	0.05±0.05%
25	Can (SS)	7.0±0.2	06/03/1737	53	11±2.3	12±2.4	3.0±0.6	277	572±145	2.08±1.04%	8.91±3.29%	0.06±0.19	8.70±3.30%
26	Ezine (SS)	7.0±0.2	08/02/1826	56	11±2.5	11±2.6	2.0±0.4	188	860±204	1.31±0.66%	0.80±0.75%	0.07±0.06	0.89±0.82%

Table 1. Occurence probability according to Poisson BPT and BPT+ΔCFF. The error associated has been computed by the Monte Carlo distribution.

Conditional Probability Ffrom Renewal BPT model

Statistically, the occurrence of events is represented as a point process, and the inter-event time is modelled by a probability density function (pdf). In this context, the null hypothesis is described by a uniform Poisson model, the earthquake hazard is constant in time while the pdf is a negative exponential function:

$$f(t;T_r,\alpha) = \left(\frac{T_r}{2\pi\alpha^2 t^3}\right)^{1/2} \exp\left\{-\frac{(t-T_r)^2}{2T_r\alpha^2 t}\right\} \qquad (1)$$

where t is the time elapsed since the latest characteristic earthquake, and Tr is the mean inter-event time, i.e. the average recurrence time. The Brownian Passage-Time (BPT) pdf (Matthews et al., 2002) is given by:

$$f(t) = \frac{1}{T_r}\exp\left\{-\frac{t}{T_r}\right\} \qquad (2)$$

Where α is the coefficient of variation (also known as the aperiodicity) of the distribution. The coefficient of variation is the standard deviation of inter-event times between large events that rupture all or most of a given fault segment divided by the mean repeat time for that segment. It is a key parameter in time-varying probability calculations.

The probability for the occurrence of a new event in a given time window Δt, conditional on no events occurring before time t, is obtained from the density distribution of the inter-event times:

$$\Pr[t < T \le t+\Delta t | T > t] = \frac{\Pr[t < T \le t+\Delta t]}{\Pr[t < T]} = \frac{\int_t^{t+\Delta t} f(u)du}{1-\int_0^t f(u)du} \qquad (3)$$

By means of equation (3), we have computed the probability of occurrence for a characteristic earthquake on each fault segments under the Poisson and BPT distributions, for the next 50 yrs. starting on January, 1 2014. The computation starts at the time of occurrence of the first characteristic earthquake on each segment and the elapsed time is reset to zero upon the occurrence of every subsequent event.

The computations are repeated 100 times in a Monte Carlo procedure by randomly drawing both the inter-event time and the coefficient of variation from a normal (or Gaussian) distribution within their respective uncertainties. Among the 100 outcomes, we have considered the 16th, 50th and 84th percentiles.

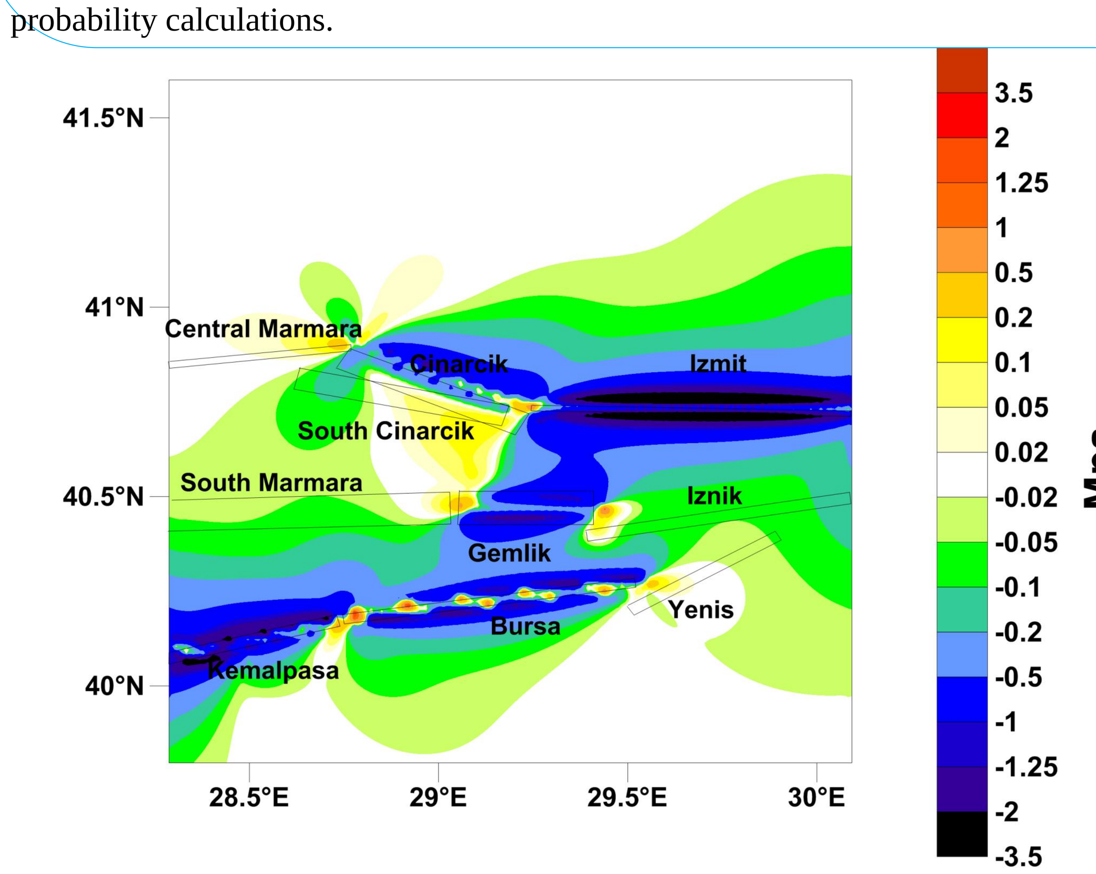

Figure 3. Map of the Coulomb Stress changes ΔCFF generated by all the earthquakes following the September 2, 1754 event in the seismogenic area of South Cinarcik fault, South of Instanbul, at a depth of 3.5 km. ΔCFF values are computed on the basis of the fault mechanism of the concerned earthquake.

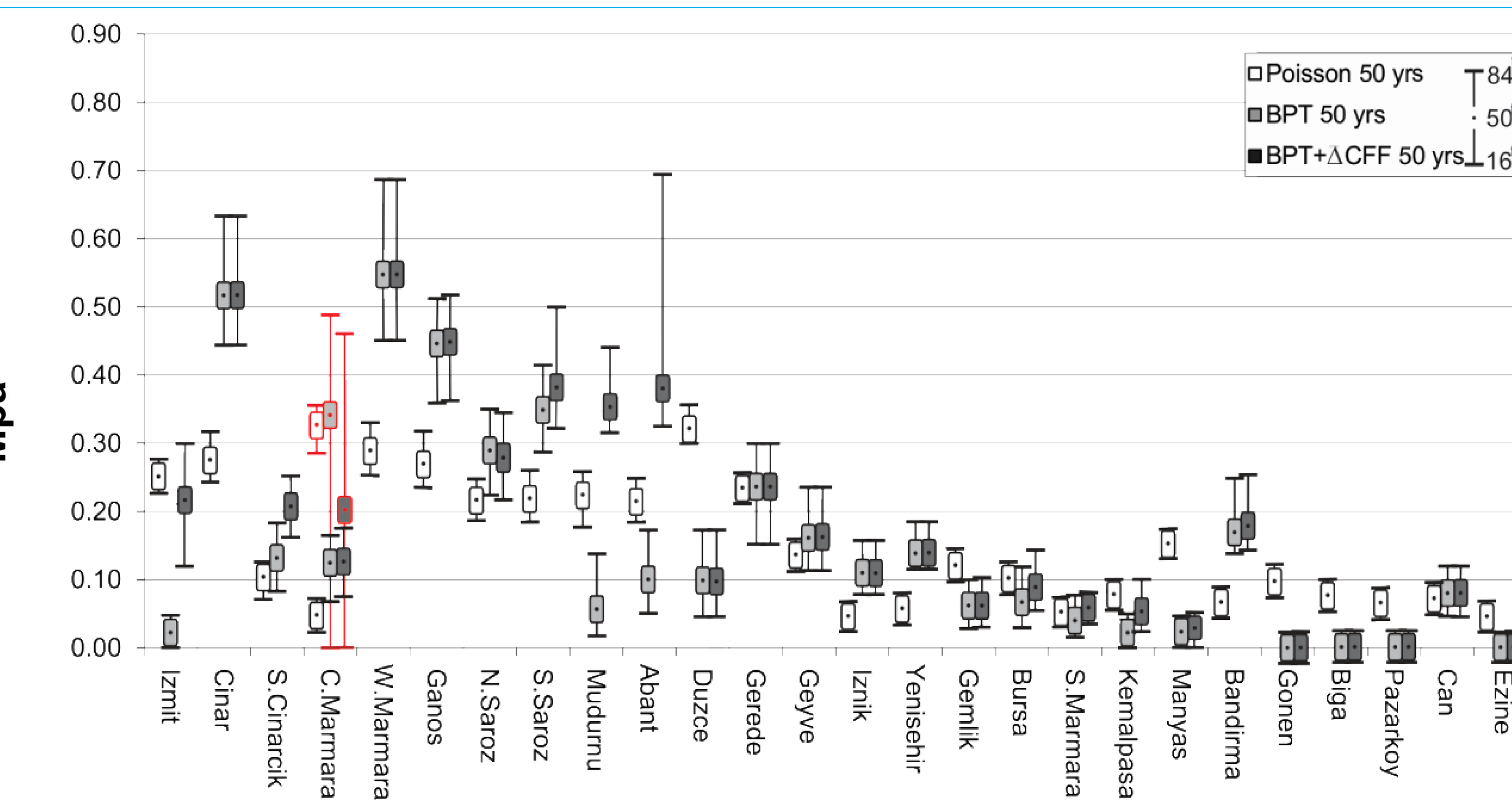

Figure 2. Occurrence Probability of a characteristic earthquake on each fault segment over 50 years starting on January 1, 2014 according to Poisson, BPT and BPT+ΔCFF. For each model the probability values related to 16th, 50th and 84th percentiles are shown in the plot.

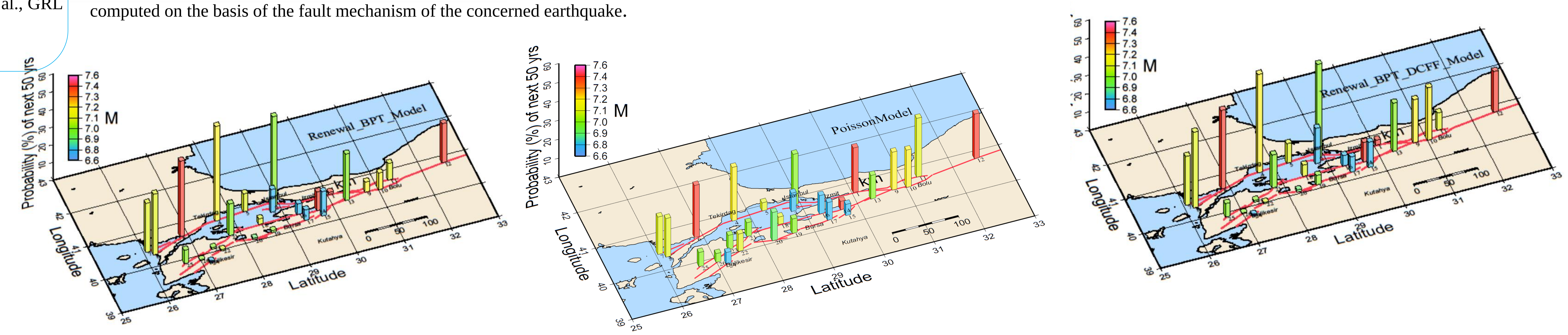

Figure 4. Probability of occurrence of the next characteristic quake over 50 yrs starting on January 1, 2014 according to Poisson, BPT and BPT +ΔCFF models. The largest values of occurrence under the BPT model will be for West Marmara and Cinarcik faults, in the northern part of Marmara Sea, near the city of Istanbul. These faults have a BPT probability equal to 56.65±11.95% and 54.5 ± 9.60% , respectively. The corresponding Poisson probabilities are 6.40 ± 3.20% and 5.408 ± 2.70%. The BPT probabilities for the Izmit (#1) and Duzce (#11) faults are lower than the Poisson values due to the short elapsed time (15 years) after the occurrence of their last characteristic events.

Summarizing we can say that:

- The largest values of the Poisson probability for the next 50 yrs. are on those faults that have a high annual mean rate of earthquake occurrence (that is, low values of recurrence time) and high slip rate, e..g. Duzce (#11), West Marmara (#5) and Cinarcik (#2) with a recurrence time of 130, 144 and 154 yrs, respectively.
- The BPT probability for the next 50 yrs. is larger than the Poisson probability when the Elapsed Time is relevant respect to the Recurrence Time (e.g., Cinarcik (#2), Central Marmara (#4), West Marmara (#5), North Saros (#7), South Saros (#8), Geyve (#13), Iznik (#14), Yenisehir (#15), and Bandirma (#21)). The largest value of the BPT probability for the next 50 yrs. are for West Marmara (Elapsed Time 458 yrs., Recurrence Time 144 yrs.) and Cinarcik faults (Elapsed Time 248 yrs., Recurrence Time 154 yrs.).
- The BPT probability is smaller than the Poisson probability when the Elapsed Time is short respect to the Recurrence Time (Izmit (#1), Mudurnu (#9), Abant (#10), Duzce (#11), Gemlik (#16), Bursa (#17), Kemalpasa (#19), Manyas (#20), Gonen (#22), Biga (#23), Pazarkoy (#24), Ezine (#26)) .
- The positive effect of ΔCFF is relevant for Izmit (#1), South Cinarcik (#3), South Saros (#8), Mudurnu (#9), Abant (#10), Bursa (#17), South Marmara (#18), Kemalpasa (#19), Manyas (#20). The maximum effect is for Mudurnu (#9) (BPT 6.71%, BPT +ΔCFF 24,4%) and Abant (#10) (BPT 10.40%, BPT +ΔCFF 29.5%). These faults have received the stress transfer from Izmit and Duzce earthquakes (1999).
- The hazard on Instanbul city is mainly due to the Central Marmara (#4), Cinarcik (#2) and South Cinarcik (#3)faults. The probabilities under BPT model are 11.08±3.72%, 54.50±9.60% and 13.93±4.87%, respectively. Taking into account the stress change effect these probabilities are modified into 11.98±3.92%, 54.65±9.65% and 21.25±5.15%, respectively. The combined probability that at least one of these three faults will rupture in the next 50 yrs. is 68.57%.