Additional information for the paper 'Entropy of seismic electric signals: Analysis in natural time under time-reversal' after its initial submission

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After the submission of the paper, three strong earthquakes with magnitude around 6.0-units occurred on October 17 and October 20, 2005, with epicenters in the Aegean Sea, at a distance *only* 100km from MYT station at which the intense signals M_1 to M_4 -analyzed in the main text- have been recorded. This confirms experimentally the classification of these signals as Seismic Electric Signals (SES) that was made well in advance. Moreover, we show that, if we follow the procedure described in [1,2], the analysis in the natural time of the seismicity after the SES initiation allows the estimation of the time window of the impending earthquakes with good accuracy.

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On October 17, 2005 two strong earthquakes (EQs) with magnitude around 6.0-units occurred at 05:45:20 and 12:46:57 UT with epicenters (according to USGS) at 38.15^oN,26.68^oN and 38.13^oN,26.65^oN, respectively (see Fig.1). At the same epicenter, a third almost equally strong earthquake occurred at 21:40 UT on October 20,2005. All the three epicenters lie at a distance of around 100km from Lesvos island, at which the MYT station -on the dipoles of which the intense signals M_1 to M_4 (Fig.1(a),(b) of the main text) have been recorded- is located. This verifes that these signals are actually Seismic Electric Signals (SES) as classified in advance (i.e., upon the initial submission of the paper on April 16,2005).

We now follow the procedure described in Refs.[1, 2], in order to investigate whether the time window of the impending strong EQs could have been estimated. We consider either the area A:$N^{39.5}_{37.0}E^{28.0}_{25.5}$ or the area B:$N^{39.5}_{37.5}E^{28.0}_{26.0}$, which surround the EQ epicenters and the MYT station (see Fig.1), and study how the seismicity evolved after the SES initiation. If we set the natural time for seismicity zero at the initiation of the concerned SES activities, we form time series of seismic events in natural time for various time windows as the number N of consecutive (small) EQs increases. We now compute[3] the normalized power spectrum [1, 2] in natural time $\Pi(\phi)$ for each of the time windows and the results are depicted in Fig.2. As examples we consider in this figure the case of area B with magnitude threshold (herafter referring to the local magnitude M_L or the 'duration' magnitude M_D) $M_{thres} = 3.4$ (upper) and the case of area A with $M_{thres} = 3.6$ (lower). In the same figure, we plot in blue the power spectrum obeying the relation

$$\Pi(\omega) = \frac{18}{5\omega^2} - \frac{6\cos\omega}{5\omega^2} - \frac{12\sin\omega}{5\omega^3} \tag{1}$$

which holds[1, 4, 5] when the system enters the *critical* stage ($\omega = 2\pi\phi$, where ϕ stands for the natural frequency[1, 4–6]). The (red) numbers in this figure denote the number of small earthquakes that occurred after the initiation of the SES activities. An inspection of Fig.2 reveals that the red line approaches the blue line as N increases and a *coincidence* occurs at the last small event which had a magnitude 3.6 (see also below) and occurred at 04:31 UT on October 17, 2005, i.e., roughly one hour before the first strong EQ. To ensure that this coincidence is a *true* one[1, 2, 5, 6] we also calculate the evolution of κ_1,S and S_- (cf. κ_1 stands for the variance $\kappa_1 \equiv \langle\chi^2\rangle - \langle\chi\rangle^2$ as explained in Refs.[1, 4]) and the results are depicted in Fig.3 for three magnitude thresholds 3.4, 3.5 and 3.6 for both areas. The conditions for a coincidence to be considered as *true* are the following (e.g., see Ref.[1], see also [2, 6]): First, the 'average' distance $\langle D\rangle$ between the empirical and the theoretical $\Pi(\phi)$(i.e., the red and the blue line, respectively, in Fig.2) should be[1, 2, 6] smaller than 10^{-2}, see Fig.4 where we plot $\langle D\rangle$ versus either the natural time in Fig.4(a) or the conventional time in Fig.4(b) for the aforementioned two areas and the three magnitude thresholds (hence six combinations were studied in total). Second, it was experienced that in the examples observed to date[1, 2, 6], a few events *before* the coincidence leading to the mainshock, the evolving $\Pi(\phi)$ should approach that of Eq.(1), i.e., the blue one in Fig.2 , from *below* (cf. This equivalently means that during this approach the κ_1-value should decrease as the number of events increases). In addition, both values S and S_- should be smaller than S_u at

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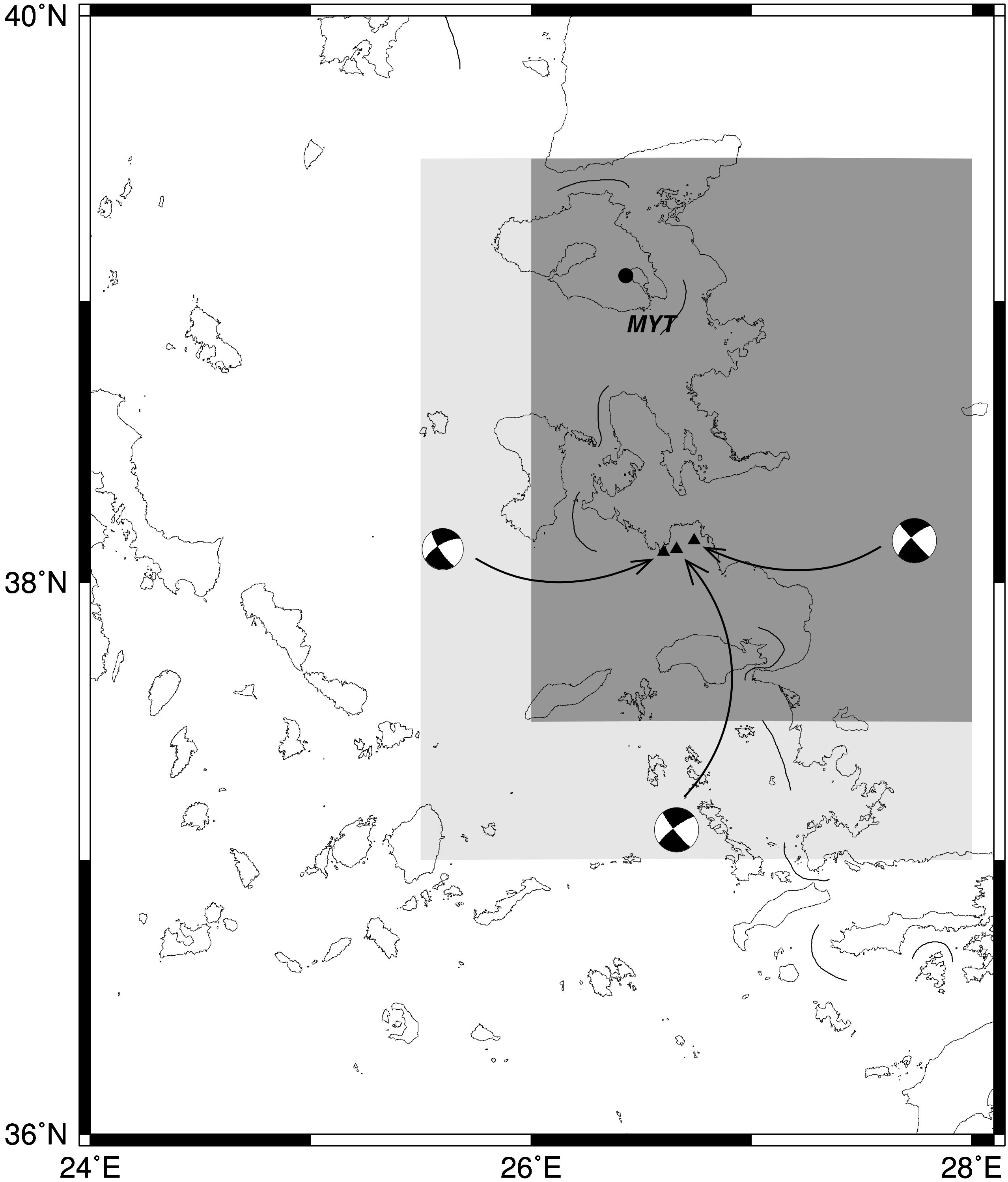

FIG. 1: Map of the area surrounding the measuring station of MYT and the epicenters of the three strong EQs that occurred on October 17 and October 20,2005. The earthquake mechanisms of all three EQs are also shown. The seismicity subsequent to the SES initiation has been studied in the gray shaded areas (these are designated A and B for the large and the small area, respectively).

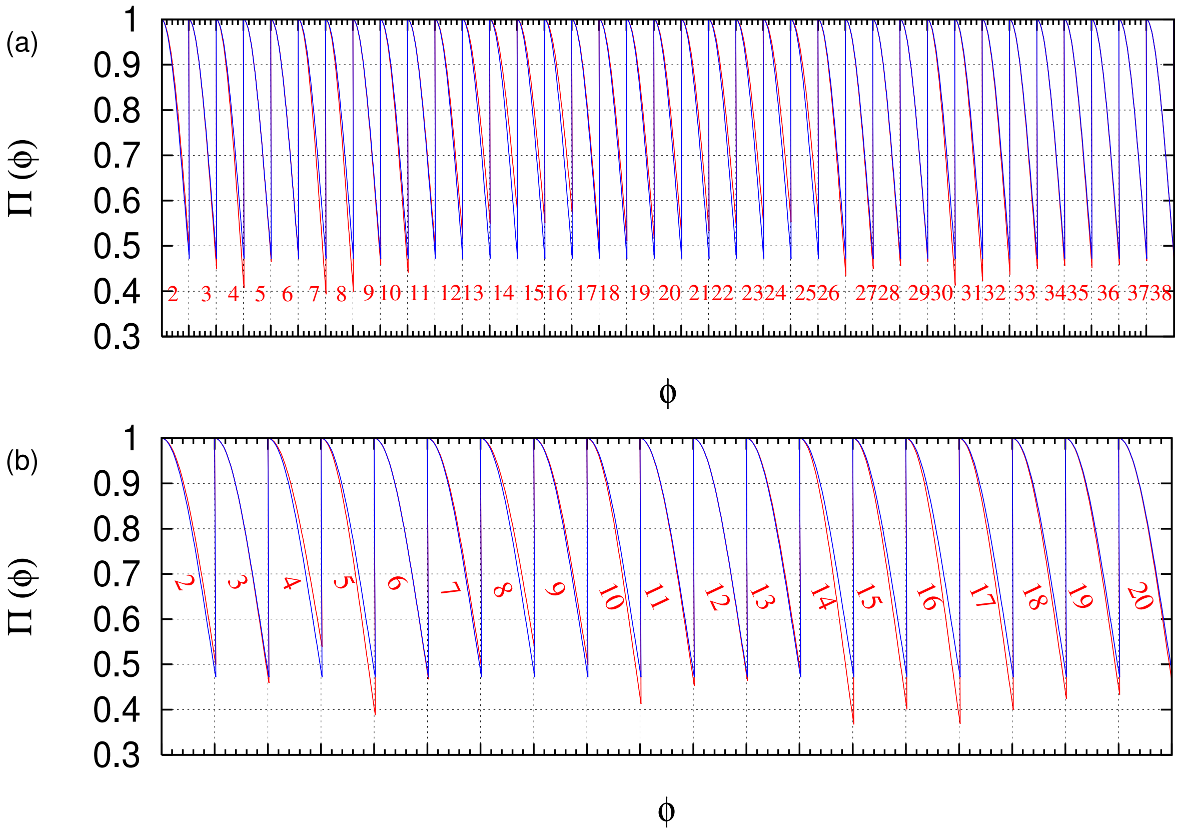

FIG. 2: (color)The normalized power spectrum(red) $\Pi(\phi)$ of the seismicity as it evolves event by event after the initiation of the SES activities M_1 to M_4. The two examples presented area B $M_{thres} = 3.4$ (a) and area A $M_{thres} = 3.6$ (b). The number of events(earthquakes), after the initiation of the SES activity M_1 that have been considered in the calculation of $\Pi(\phi)$ is indicated by the red numbers. In each case only the spectrum in the area $\phi \in [0, 0.5]$ (for the reasons discussed in Refs.[1, 2]) is depicted (separated by the vertical dotted lines), whereas the $\Pi(\phi)$ of Eq.(1) is depicted by blue color. The minor horizontal ticks for ϕ are marked every 0.1.

the coincidence. Finally, since the process concerned is self-similar (critical dynamics), the time of the occurence of the (true) coincidence should *not* change, in principle, upon changing either the (surrounding) area or the magnitude threshold used in the calculation. Note that in Fig.4, upon the occurence of the aforementioned last small event, in both areas A and B for the two lower magnitude thresholds, i.e., 3.4 and 3.5, as well as for the (large) area A with $M_{thres} = 3.6$, their $\langle D\rangle$ values become smaller than 10^{-2}. Only when the magnitude threshold is 3.6 in the (small) area B, the quantity $\langle D\rangle$ results in a larger value, i.e., $\langle D\rangle \approx 1.7 \times 10^{-2}$ which may be understood in the frame that when the magnitude threshold is larger and the area smaller (thus reflecting a smaller number of events), the accuracy of the calculation (due to the *coarse graining*) becomes less. Hence, this coincidence (i.e., upon the occurrence of the last small event) can be considered as true.

We now discuss, for the reader's convenience, three examples of coincidences in Fig.2(b) that are not true. First, an early coincidence that seems to exist at the case marked '3' (corresponding to an event that occurred at 11:55 UT on June 23), cannot be considered as true for three reasons: The red line approaches the blue one from above (compare '2' and '3'), the $\Pi(\phi)$ value is calculated with a small number of events (three only), and we do not obtain the same occurrence time of the coincidence when considering smaller magnitude thresholds (see Fig.5). Second, the coincidence marked '6' in Fig.2(b) (which corresponds at the event that occurred at 04:27 UT on June 24), cannot be considered as true, because we do not obtain, in a similar fashion as in the previous case, the same occurrence time of the coincidence when considering a smaller magnitude threshold(i.e., see Fig.5 in which the case of area A with $M_{thres} = 3.4$ (blue asterisks) minimizes $\langle D\rangle$ one event before that corresponding to '6'). A further investigation of this coincidence was made by studying an additional area, i.e., the (intermediate) area $N^{39.5}_{37.0}E^{28.0}_{26.0}$ with $M_{thres} = 3.4$, and the results are given in black in Fig.5. They show that, when the coincidence '6' occurs (on June 24), $\langle D\rangle$ exceeds 10^{-2}. Third, as for the case marked '12' in Fig.2(b), it corresponds to an event that occurred on July 11; Fig.5 shows that $\langle D\rangle$ exceeds 10^{-2} for all other (five) combinations of areas and magnitude thresholds.

Since the strong EQs occurred in the border between Greece and Turkey, the seismicity catalogues of neither Greek

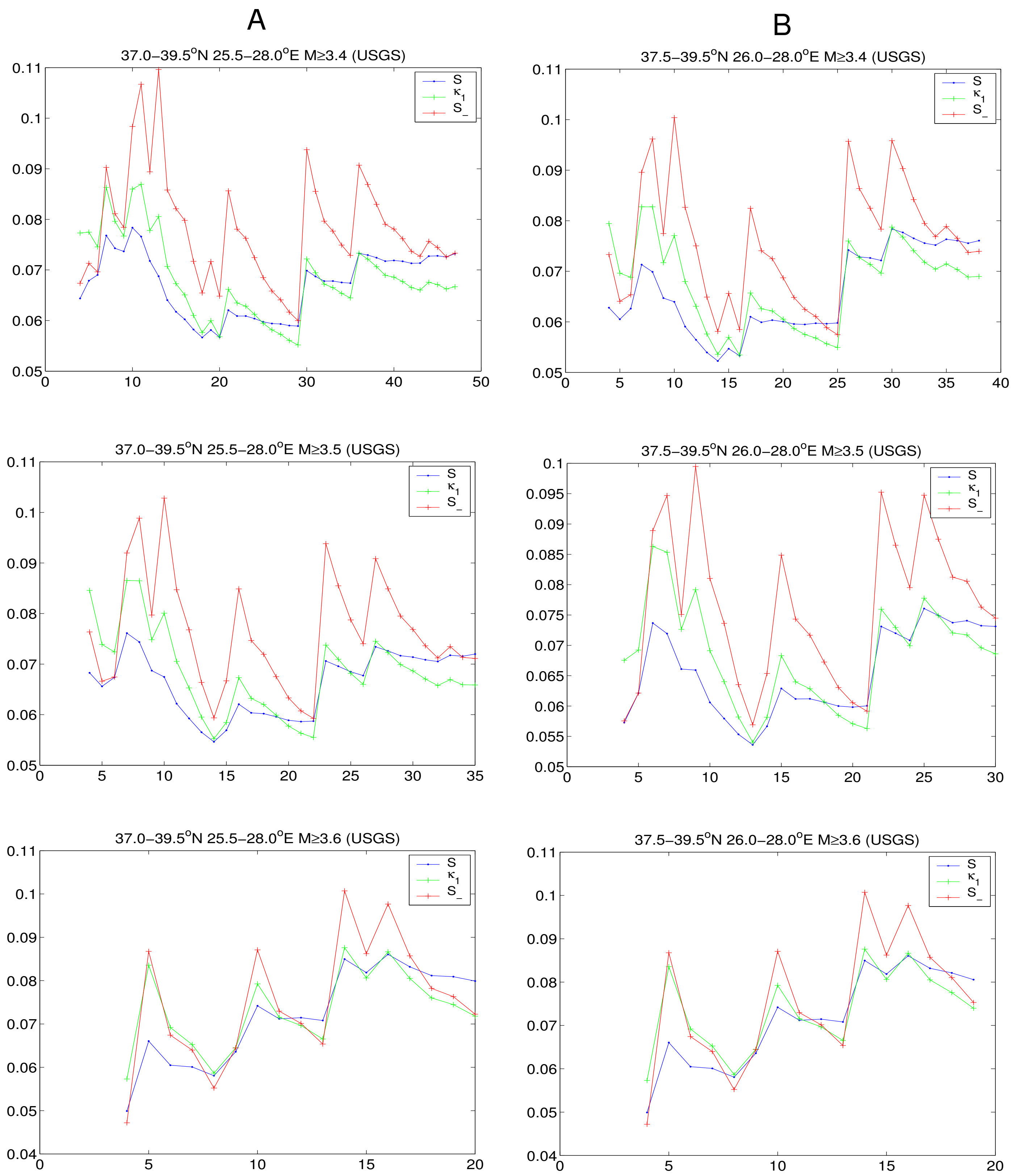

FIG. 3: (color)Evolution of κ_1, S and S_- for various magnitude thresholds for the two areas A and B.

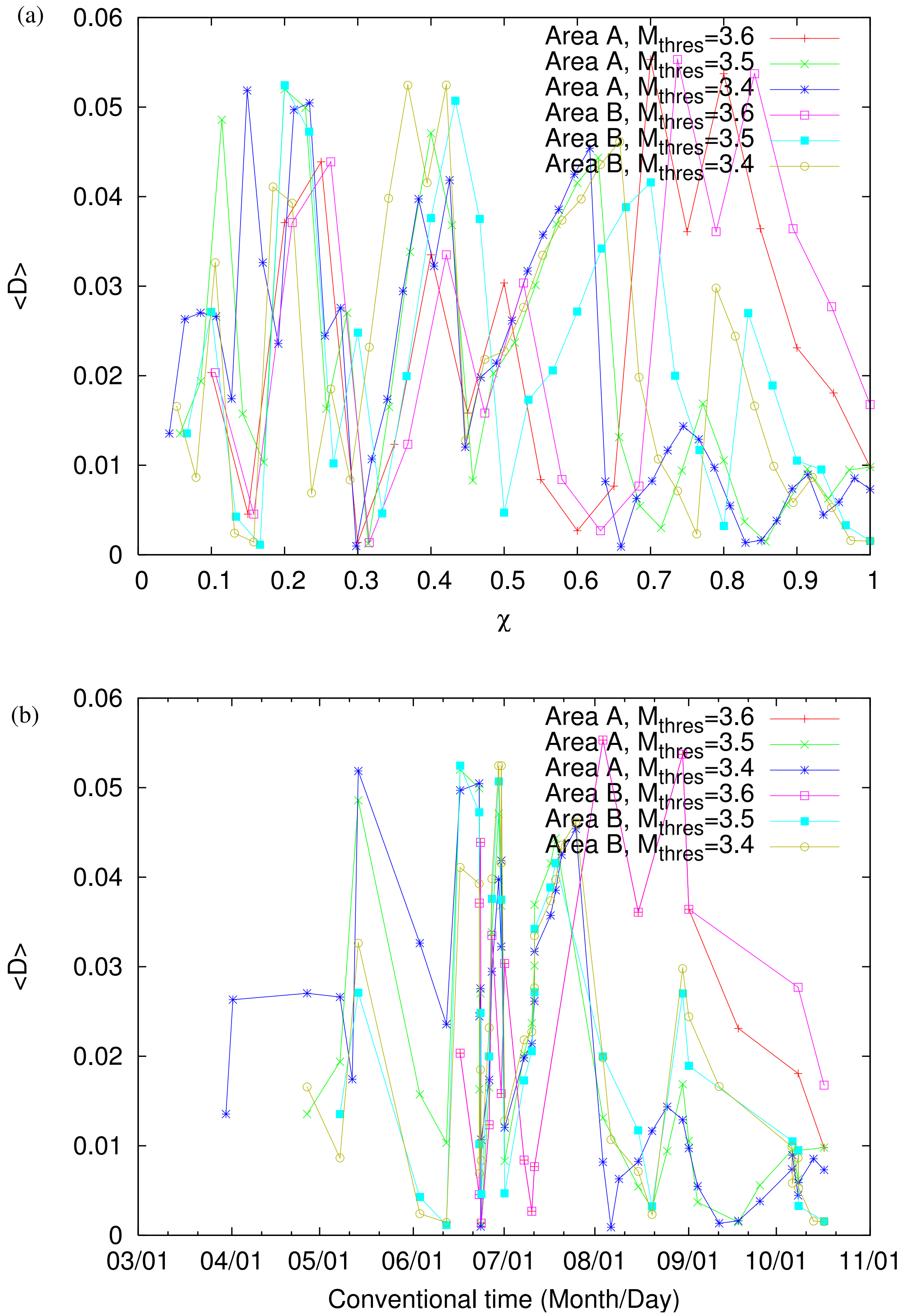

FIG. 4: (color)The evolution of the average distance $\langle D \rangle$ between the calculated and the theoretical $\Pi(\phi)$ curves versus natural time (a) and conventional time (b). The calculation of $\langle D \rangle$ is made upon the occurrence of every consecutive earthquake when starting the calculation after the initiation of the SES activities (depicted in Fig.1(a),(b) of the main text) for each of the two areas A and B by considering three magnitude thresholds 3.4, 3.5 and 3.6.

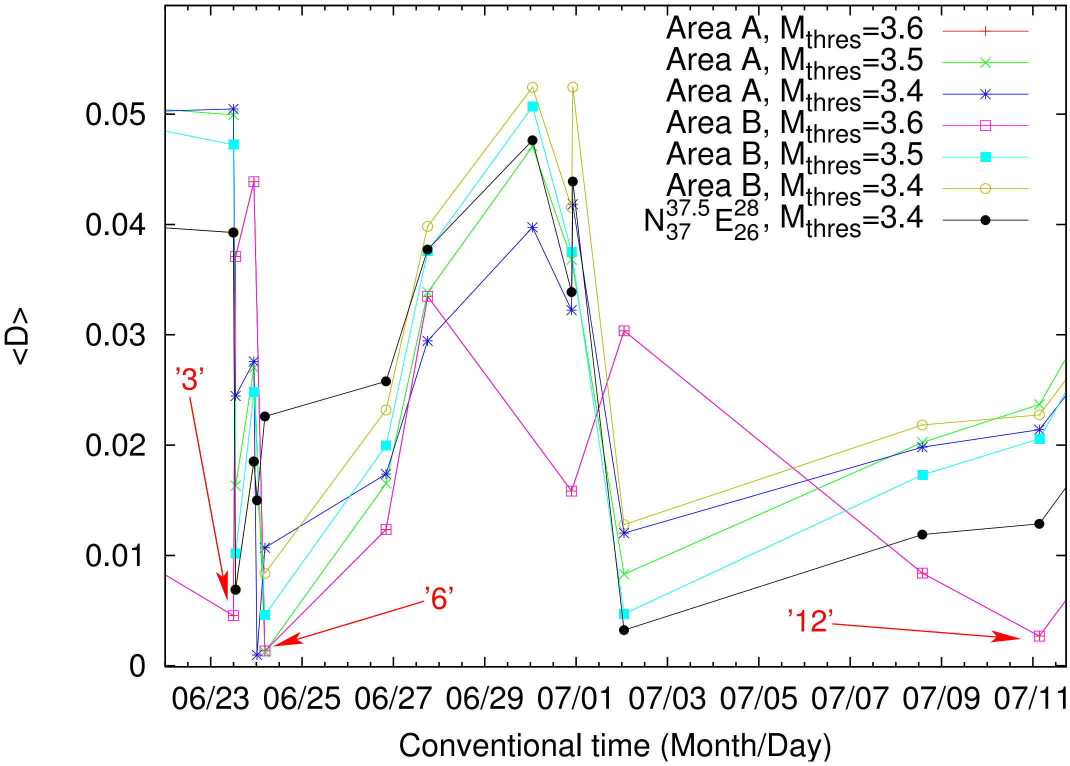

FIG. 5: (color)Excerpt of Fig.5(b) for the period June 22,2005 to July 11,2005, showing that the coincidences for the cases (marked in Fig.2(b)): '3' (occurring on the 1st EQ of June 23) , '6' (occurring on June 24) and '12' (occurring on July 11) do not coincide with those in smaller magnitude thresholds. The arrows indicate the coincidences '3', '6' and '12' in Fig.2(b).

nor the Turkish Institutes can be considered as complete for small magnitudes. Hence, we preferred here to make the calculations by relying on the United States Geological Survey (USGS) catalogue (see Table I). Irrespective if we use the seismicity in the area A:$N^{39.5}_{37.0}E^{28.0}_{25.5}$ or in the smaller area B:$N^{39.5}_{37.5}E^{28.0}_{26.0}$, the coincidence occurs, as mentioned above, upon the occurence of the last small event almost 1 hour before the first strong EQ. The magnitude of this small event was reported to be 3.6 by the European-Mediterranean Seismological Centre (EMSC) (see the corresponding announcement in Fig. 6). Note that if we take the magnitude of this EQ to be somewhat larger (e.g., 3.9), then the uppermost right box in Fig.3 (which has been plotted for magnitude threshold 3.4) suggests that the coincidence might have occurred on the last but one event, i.e., on October 13,2005 and hence almost three days before the first strong EQ (this is also found in the study of the (intermediate) area $N^{39.5}_{37.0}E^{28.0}_{26.0}$ mentioned above). Note, however, that *irrespective* if we consider that the coincidence occurred either one hour or three days before the first big EQ, this time window is appreciably shorter compared to the time elapsed from the recording of the SES activities (until the occurence of the strong earthquake activity) and, in this sence, it can be characterized as having been determined with good accuracy.

The probability that these events, i.e., the SES activities and the three strong EQs, occurred as random events is estimated as follows: The time Δt elapsed from the recording of the SES activities until the strong EQs occurrence is $\Delta t \approx$ 7months. When searching[7] the seismicity in that area, we find that a magnitude 6.0-units EQ occurs, on the average after a period $T \approx$ a few tens of years. Hence, the probability that a *single* magnitude 6.0 EQ will occur by chance within the time Δt is $\Delta t/T \lesssim 5\%$. Thus, the corresponding probability for a sequential chancy occurrence of *three* consecutive EQs of magnitude 6.0 (within a few days) is obviously drastically smaller then 5% . (Furthermore, the probabality for a chancy occurrence of a magnitude 6.0 EQ within the short time period elapsed from the occurence of the *true coincidence* until the initiation of the strong EQ activity on October 17,2005, is orders of magnitude smaller than 5%.)

[1] P. A. Varotsos, N. V. Sarlis, and E. S. Skordas, Practica of Athens Academy **76**, 294 (2001).

EMSC relocation in GSE format

```
BEGIN GSE2.0
MSG_TYPE DATA
MSG_ID 051017043127 EMSC
DATA_TYPE BULLETIN GSE2.0

EVENT 20051017043127
  Date       Time       Latitude Longitude   Depth   Ndef Nsta Gap    Mag1  N    Mag2  N     Mag3  N  Author       ID
      rms   OT_Error      Smajor Sminor Az        Err   mdist  Mdist    Err       Err       Err     Quality

2005/10/17 04:31:27.3    38.1899  26.7128    20.0     44   41   80  ML 3.6                    CSEM       GSP66
     0.76   +-  0.12       3.4    2.5   84             0.32   5.90                       a i uk

AEGEAN SEA
Sta     Dist  EvAz   Phase      Date        Time    TRes  Azim  AzRes  Slow  SRes Def  SNR      Amp   Per  Mag1   Mag2     ID
BLCB    0.32  52.9 m  Pg     2005/10/17 04:31:35.1   0.3                     T                       KAN
BLCB    0.32  52.9 m  Sg     2005/10/17 04:31:40.1  -0.2                     T                       KAN
SMG     0.49 168.4 a  Pn     2005/10/17 04:31:36.6  -0.1                     T                       NOA
IZM     0.49  64.7 m  Pg     2005/10/17 04:31:37.8  -0.1                     T                       KAN
AKS     1.10  51.1 m  Pn     2005/10/17 04:31:48.2  -0.1                     T                       KAN
PRK     1.11 342.0 a  Pn     2005/10/17 04:31:47.9  -0.1                     T                       NOA
BODT    1.22 157.0 m  Pn     2005/10/17 04:31:49.6  -0.3                     T                       KAN
BODT    1.22 157.0 m  Sg     2005/10/17 04:32:06.6  -2.2                     T                       KAN
MLSB    1.23 136.3 m  Pn     2005/10/17 04:31:50.7   0.6                     T                       KAN
APE     1.46 220.4 m  Pn     2005/10/17 04:31:51.3  -1.6                     T                       KAN
YER     1.63 129.6 m  Pn     2005/10/17 04:31:55.7  -0.2                     T                       KAN
EZN     1.66 349.7 m  Pn     2005/10/17 04:31:56.0  -0.2                     T                       KAN
BALB    1.71  31.8 m  Pn     2005/10/17 04:31:56.7  -0.2                     T                       KAN
CANB    1.84   8.4 m  Pn     2005/10/17 04:31:57.7  -1.1                     T                       KAN
DENT    1.88 102.6 m  Pn     2005/10/17 04:31:59.8   0.4                     T                       KAN
DST     2.05  45.9 m  Pn     2005/10/17 04:32:01.7  -0.1                     T                       KAN
LIA     2.08 325.5 a  Pn     2005/10/17 04:32:02.0   0.6                     T                       NOA
DALT    2.09 132.2 m  Pn     2005/10/17 04:32:02.5   0.2                     T                       KAN
LPK     2.18   1.0 m  Pn     2005/10/17 04:32:03.8   0.2                     T                       KAN
KHL     2.22  85.7 m  Pn     2005/10/17 04:32:04.9   0.6                     T                       KAN
EDC     2.33  22.2 m  Pn     2005/10/17 04:32:06.1   0.4                     T                       KAN
BNT     2.35  22.6 m  Pn     2005/10/17 04:32:05.0  -1.0                     T                       KAN
FETY    2.44 128.7 m  Pn     2005/10/17 04:32:07.2   2.8                     T                       KAN
ORLT    2.51  41.8 m  Pn     2005/10/17 04:32:08.4   0.0                     T                       KAN
MRMT    2.51  15.6 m  Pn     2005/10/17 04:32:08.6   0.3                     T                       KAN
MFT     2.63   9.4 m  Pn     2005/10/17 04:32:09.3  -0.8                     T                       KAN
KARP    2.66 172.1 a  Pn     2005/10/17 04:32:09.3  -0.2                     T                       NOA
ALT     2.80  71.0 m  Pn     2005/10/17 04:32:12.3  -0.2                     T                       KAN
ELL     2.92 118.5 m  Pn     2005/10/17 04:32:14.7   0.4                     T                       KAN
ISP     3.03  95.8 mdi P     2005/10/17 04:32:15.3  -0.3                     T                       GSRC
ISP     3.03  95.8 m  Pn     2005/10/17 04:32:16.0   0.2                     T                       KAN
NPS     3.05 197.2 a  Pn     2005/10/17 04:32:15.6   0.8                     T                       NOA
RDO     3.09 343.3 a  Pn     2005/10/17 04:32:15.8   0.5                     T                       NOA
YLV     3.14  40.1 m  Pn     2005/10/17 04:32:17.8   0.4                     T                       KAN
BCK     3.15 102.2 m  Pn     2005/10/17 04:32:16.8  -0.8                     T                       KAN
CTT     3.24  23.6 m  Pn     2005/10/17 04:32:18.4  -0.3                     T                       KAN
BADT    3.24  34.2 m  Pn     2005/10/17 04:32:18.4  -0.3                     T                       KAN
VLI     3.34 245.1 a  Pn     2005/10/17 04:32:20.0   1.2                     T                       NOA
ESKT    3.49  66.3 m  Pn     2005/10/17 04:32:22.7   0.2                     T                       KAN
EDRB    3.65   0.4 m  Pn     2005/10/17 04:32:24.5  -0.1                     T                       KAN
KIZT    4.11  78.7 m  Pn     2005/10/17 04:32:31.2  -0.1                     T                       KAN
MDU     4.17  55.5 m  Pn     2005/10/17 04:32:32.4   0.6                     T                       KAN
BRTR    5.61  72.0 m i P     2005/10/17 04:32:52.8   0.6                     T                       GSRC
IKL     5.90 107.2 m  Pn     2005/10/17 04:32:56.6   0.1                     T                       KAN

STOP
```

FIG. 6: The detailed European-Mediterranean Seismological Centre (EMSC) report for the last small event (M_L=3.6) that occurred almost one hour before the first strong EQ.

TABLE I: The United States Geological Survey (USGS) catalogue for the area A under discussion together with the last event reported by EMSC (see Fig.6).

No	Year	Month	Day	Hour	Min	Sec.	Lat.(°N)	Lon.(°E)	Depth	M	Source
1	2005	3	23	8	22	55.14	39.034	27.991	16	3.4	MLATH
2	2005	3	30	13	57	46.38	38.782	25.782	56	3.4	MDATH
3	2005	4	1	21	41	39.5	38.73	25.84	26	3.5	MDATH
4	2005	4	26	18	22	8.9	39.05	26	10	3.5	MDATH
5	2005	5	7	19	4	40.31	39.492	26.158	12	3.5	MDATH
6	2005	5	11	22	3	3.5	38.77	25.56	31	3.4	MLATH
7	2005	5	13	22	30	29.7	38	26.68	12	3.7	MLATH
8	2005	6	3	13	48	56.8	38.78	26.54	54	3.5	MDATH
9	2005	6	12	12	43	46.1	38.01	27.61	5	3.5	MDATH
10	2005	6	17	2	47	54.6	38.06	27.4	27	3.8	MDATH
11	2005	6	23	11	55	39.2	37.8	26.76	25	3.9	MLATH
12	2005	6	23	13	7	6.2	37.78	26.81	17	3.6	MDATH
13	2005	6	23	22	44	16.7	37.76	26.7	19	4.1	MLATH
14	2005	6	24	0	21	33	37.36	26.87	22	3.4	MDATH
15	2005	6	24	4	27	8.6	37.76	26.72	45	3.8	MDATH
16	2005	6	26	20	7	26.7	37.77	26.77	18	3.8	MLATH
17	2005	6	27	17	59	51.6	38.87	27.67	23	3.6	MDATH
18	2005	6	30	1	3	31	37.68	26.8	22	3.5	MDATH
19	2005	6	30	21	34	53.8	37.8	26.78	19	3.8	MLATH
20	2005	6	30	22	14	52.6	37.73	26.86	20	3.4	MDATH
21	2005	7	2	1	9	24.51	37.77	26.731	10	4	MLATH
22	2005	7	8	13	56	36.9	37.74	27.57	10	3.6	MDATH
23	2005	7	11	3	23	30.2	37.79	27.47	23	3.7	MDATH
24	2005	7	12	0	47	45.4	37.8	27.59	24	3.6	MDATH
25	2005	7	12	0	55	19.5	37.83	27.6	10	3.5	MDATH
26	2005	7	17	11	6	39.4	37.75	26.69	5	3.5	MDATH
27	2005	7	19	3	56	52	38.754	27.829	21	3.5	MDATH
28	2005	7	21	3	12	35	37.774	27.574	6	3.4	MDATH
29	2005	7	25	21	56	48	38.764	27.721	17	3.4	MDATH
30	2005	8	3	23	52	59	39.32	26.88	28	4.1	MLATH
31	2005	8	6	16	40	7.7	38.88	26.34	24	3.4	MDATH
32	2005	8	9	9	11	11.4	37.06	27.89	54	3.4	MDATH
33	2005	8	15	20	51	22	38.084	26.314	12	3.6	MLATH
34	2005	8	20	11	53	17	38.599	26.041	29	3.5	MDATH
35	2005	8	25	13	9	10	37.222	28	24	3.5	MDATH
36	2005	8	30	17	39	46.43	39.141	27.9	16	4	MDATH
37	2005	9	1	19	24	56.4	37.77	26.75	19	3.6	MDATH
38	2005	9	4	18	14	37.8	38.75	25.59	38	3.5	MDATH
39	2005	9	11	23	30	47.3	39.24	26.62	24	3.4	MDATH
40	2005	9	18	9	54	13	37.05	27.88	24	3.6	MDATH
41	2005	9	25	16	25	38.38	38.874	25.824	76	3.5	MDATH
42	2005	10	6	9	52	14.8	37.69	27.79	30	3.4	MDATH
43	2005	10	6	12	23	5.3	37.81	26.7	31	3.5	MDATH
44	2005	10	8	10	33	29	38.67	27.78	45	3.7	MDATH
45	2005	10	8	15	36	11.4	38.88	27.47	45	3.5	MDATH
46	2005	10	13	15	33	8.2	38.32	26.84	25	3.4	MDATH
47	2005	10	17	4	31	26	38.189	26.632	17	3.9*	MLATH

*This magnitude was reported by EMSC to be 3.6 (see Fig. 6)

[2] P. Varotsos, N. Sarlis, H. Tanaka, and E. Skordas, Phys. Rev. E **72**, 041103 (2005).
[3] As stated in Section I of the main text Q_k is proportional to the seismic moment M_0. Following Ref.[1,2,5], for the reasons of this calculation the formulae $M_0 = 10^{M_L+10.5}$(Nm), for $M_L \leq 3.6$ and $M_0 = 10^{1.5M_L+8.7}$(Nm), for $3.6 < M_L \leq 5.0$ proposed by the Global Seismological Services were used.
[4] P. A. Varotsos, N. V. Sarlis, and E. S. Skordas, Phys. Rev. E **66**, 011902 (2002).
[5] P. Varotsos, N. Sarlis, and E. Skordas, Acta Geophys. Pol. **50**, 337 (2002).
[6] P. Varotsos, *The Physics of Seismic Electric Signals* (TERRAPUB, Tokyo, 2005).
[7] See the United States Geological Survey (USGS) earthquake search web page `http://neic.usgs.gov/neis/epic/epic.html` for the relevant seismic catalogues.