The use of the Earth tide-seismicity compliance parameter maps for earthquake risk mitigation

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Abstract

Based on the results of our investigations, which indicate a tidal triggering effect on earthquakes when the stress in the focal area is near the critical level, we prepare yearly maps of the earth tide-seismicity *p*. It is shown that the earth tide-seismicity *p* maps points to the broader area of pending strong earthquakes within a year with a confidence level of 99.7%. Thus we suggest that earth tide-seismicity p maps may be used for earthquake risk mitigation.

1. Introduction

Applying the Hi(stogram)Cum(ulation) method, which was introduced by Cadicheanu, van Ruymbecke and Zhu (2007), we analyze the series of the earthquakes occurred in the last 50 years in seismic active areas of Greece, i.e. the areas (a) of the Mygdonian Basin(Contadakis et al. 2007), (b) of the Ionian Islands (Contadakis et al. 2012) and (c) of the Hellenic Arc (Vergos et al. 2015). The result of the analysis for all the areas indicate that the monthly variation of the earthquake frequency is in accordance with the period of the tidal lunar monthly and semi-monthly (Mm and Mf) variations and the same happens with the corresponding daily variations of the frequencies of earthquake occurrence with the diurnal luni-solar (K1) and semidiurnal lunar (M2) tidal variations. In addition the confidence level for the identification of such period accordance between earthquakes occurrence and tidal periods varies with seismic activity, i.e. the higher confidence level corresponds to time periods with stronger seismic activity. These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level (Vidale et al. 1998). Based on these results, we consider the confidence level of earthquake occurrence - tidal period accordance, which we call 'earth tide-seismicity compliance parameter *p*, as an index of tectonic stress criticality for earthquake occurrence and we construct maps of *p*'s over all the area of Greece for each year from 2000 on. It is seen that these maps indicate roughly the seismic active areas. Thus these maps, as well as those of narrower time windows, may be used in earthquake hazard estimation.

2. Method of analysis

As we have done in similar studies (Contadakis et al. 2007, Contadakis et al. 2012, Vergos et al. 2012), in order to check the possible correlation between Earth tides and earthquake occurrence we check the time of occurrence of each earthquake in relation to the sinusoidal variation of Earth tides and investigate the possible correlation of the time distribution of the earthquake events with Earth tides variation. Since the periods of the Earth tides component are very well known and quite accurately predictable in the local coordination system we assign a unique phase angle within the period of variation of a particular tidal component, for which the effect of earthquake triggering is under investigation, with the simple relation:

$$\phi_i = \{[(t_i - t_0)/T_d]\} - \text{int}\{[(t_i - t_0)/T_d]\} \times 360 \qquad (1)$$

where f_i = the phase angle of the time occurrence of the *i* earthquake in degrees,
t_i = the time of occurrence of the *i* earthquake in Modified Julian Days (MJD),
t_o = the epoch we have chosen in MJD,
T_d = the period of the particular tidal component in Julian Days.

We choose as epoch t_o, i.e. as reference date, the time of the upper culmination in Thessaloniki of the new moon of January 7, 1989 which has MJD = 47533.8947453704. Thus the calculated phase angle for all the periods under study has 0 phase angle at the maximum of the corresponding tidal component (of course M2 and S2 has an upper culmination maximum every two cycles). As far as the monthly anomalistic moon concern the corresponding epoch t_o is January 14, 1989 which has MJD = 47541.28492.

We separate the whole period in 12 bins of 30° and stack every event according to its phase angle in the proper bin. Thus we construct a Cumulative Histogram of earthquake events for the tidal period under study.

In order to check the compliance of the earthquake frequency distribution periods with the tidal periods we use the well known Shuster's test (Shuster 1897, see also Tanaka et al. 2002; 2006 and Cadicheanu et al. 2007). In Shuster's test, each earthquake is represented by a unit length vector in the direction of the assigned phase angle $\tilde{a}_i$. The vectorial sum *D* is defined as:

$$D^2 = \left(\sum_{i=1}^{N} \cos a_i\right)^2 + \left(\sum_{i=1}^{N} \sin a_i\right)^2, \qquad (2)$$

where *N* is the number of earthquakes. When α_i is distributed randomly, the probability to be the length of a vectorial sum equal or larger than *D* is given by the equation:

$$p = \exp\left(-\frac{D^2}{N}\right) \qquad (3)$$

Thus, $p < 5\%$ represents the significance level at which the null hypothesis that the earthquakes occurred randomly with respect to the tidal phase is rejected. This means that the smaller the *p* is the greater the confidence level of the results of the Cumulative Histograms is. Finally it should be noted that the total number of the shocks for each year is greater than 30 for all the years.

This means that the normal distribution approach on which Shuster test is based is valid for all the years. As an example Figure one displays the Cumulation Histogram for the Anomalistic Monthly period for the year 2013. The earth tide-seismicity compliance parameter *p* for this tidal period is 0.0, i.e. there is perfect compliance.

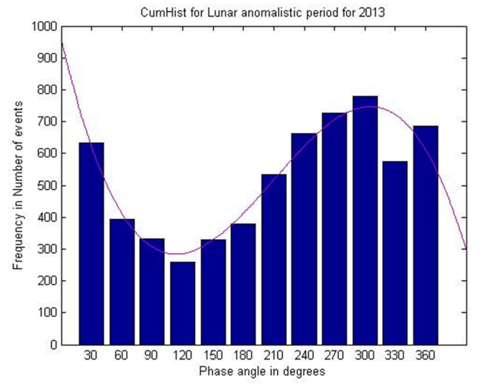

Figure 1. Cumulation Histogram for the Anomalistic Monthly period for

3. The seismicity Aegean and surrounding area and the compliance *p* maps

The high seismicity of the broader area of Aegean is controlled by the convergence of three major geological blocks: The westward motion of the Anatolian plate relative to Europe in the east, the continental collision between NW Greece-Albania and the Apulia-Adriatic platform in the west, and the subduction of the African plate under Eurasian plate along the Hellenic subduction zone to the south, result to a complicate deformation field and consequently tectonic stress field of the area. The geology and the tectonic dynamic of area has been study, and is being studied intensively (Taymaz et al. 1991; Papazachos et al. 1996; Papazachos et.al. 1999; Papazachos C. 1999; Papazachos et.al. 2002; Forough 2005). Figure 2, quoted from the Geology and Tectonics of Aegean, Chapter 2, Forough 2005, displays the compression and extension zone in the Aegean.

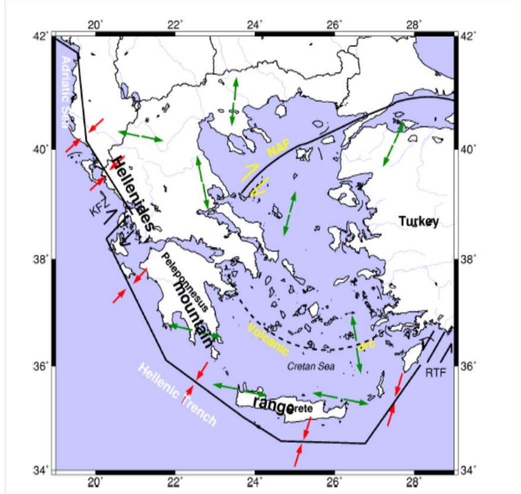

Figure 2. The compression and extension zone in the Aegean.The situation of the Aegean Volcanic Arc associated with the subduction is marked with dashed line.(quoted from the Geology and Tectonics of Aegean, Chapter 2, Forough 2005)

Figure 3 displays the epicenter of the earthquakes with M > 4.5 which has been occurred in the area of Greece between January 2005 and December 2015. For this picture we use the seismological data of the earthquake catalogue of NOA (http://www.gein.noa.gr). It is seen that most of the epicenters lie within the major faults of the area as they are shown in Figure 2.

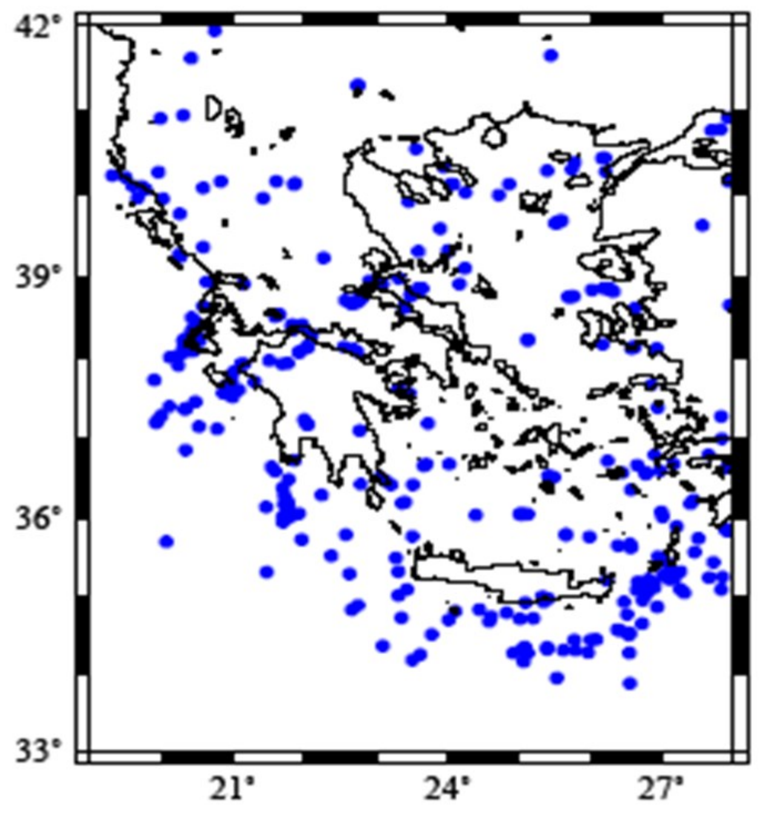

Figure 3. Earthquake with M> 4.5 occurred in the area of Greece between January

Figures 4 to 9 display the earth tide-seismicity compliance parameter p for the decade 2005-2015 of the main tidal periods. The relation of all compliance *p* distribution with earthquake epicenter distribution is obvious.

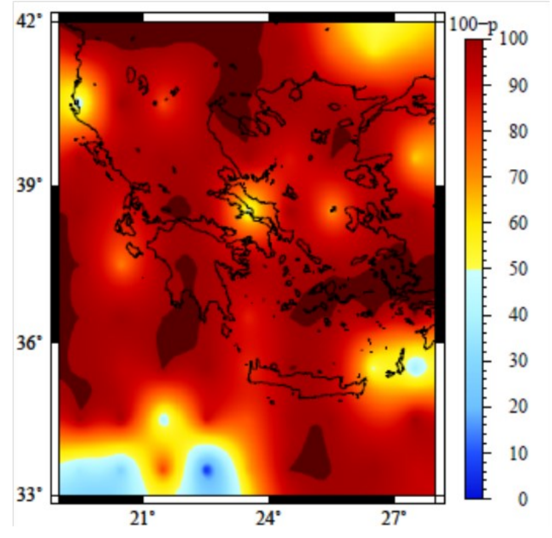

Figure 4. Compliance parameter of Monthly Synodic tidal period for the time period January, 2005 - December, 2015

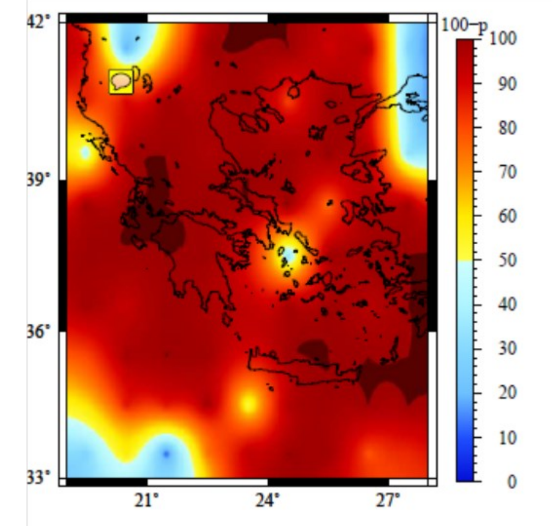

Figure 5. Compliance parameter of Monthly Anomalistic tidal period for the time period January, 2005- December, 2015.

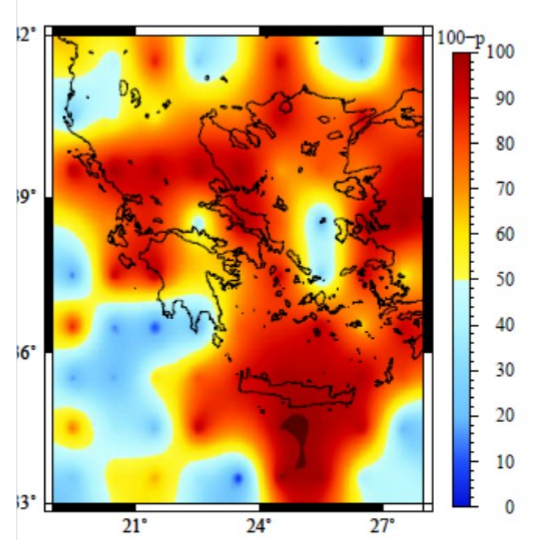

Figure 6. Compliance parameter of the Lunisolar diurnal K1 tidal period for the time period January, 2005- December, 2015.

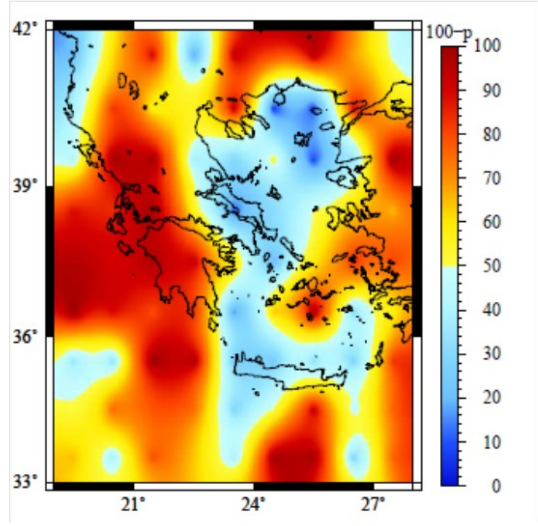

Figure 7. Compliance parameter of the Lunisolar diurnal O1 tidal period for the time period January, 2005- December, 2015.

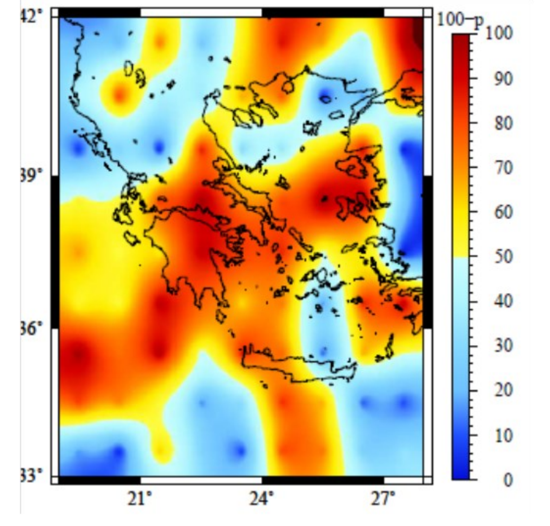

Figure 8. Compliance parameter of the Lunar semidiurnal M2 tidal period for the time period January, 2005- December, 2015

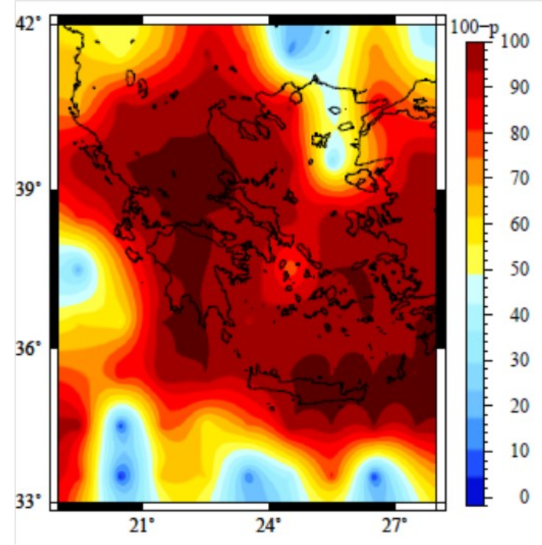

Figure 9. Compliance parameter of the Solar semidiurnal S2 tidal period for the time period January, 2005- December, 2015

3. Yearly Compliance parameter *p* of the Lunar Monthly Synodic tidal period

Figures 10 to 25 display the earth tide –seismicity compliance parameter *p* for the Lunar Monthly Synodic tidal period and the epicenters of the M ≥ 4.5 earthquakes for each year from 2000 to 2015. It is realized that the earth tide-seismicity compliance parameter *p* points to the broader area of significant earthquakes (M ≥ 4.5) with a very high consistency. More precisely, in these 15 years in the broader area of Aegean occurred 325 significant earthquakes (M ≥ 4.5) and 26 of them were strong earthquakes (M ≥ 5.5). The *p* map failed to point the broader area of 25 epicenter of earthquakes with 4.5 < M <5.5 and one epicenter of strong earthquake (M ≥ 5.5). This means that with the help of *p* maps the broader area of pending strong earthquakes within a year can be determined with a confidence level of 99.7%. Thus we suggest that earth tide-seismicity p maps may be used for earthquake risk mitigation.

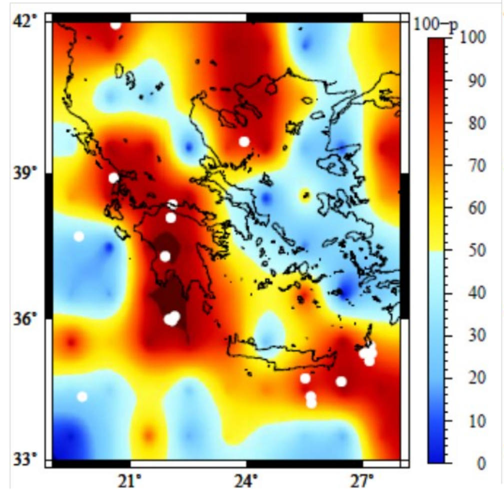

Figure 10. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2000. White marks indicate Earthquake epicenters: circles 4.5 < M < 5.5, stars M ≥ 5.5

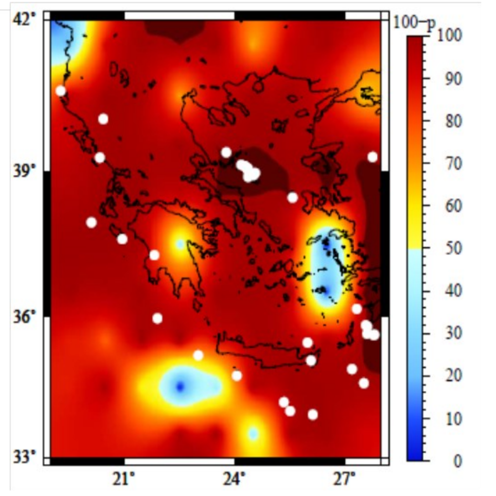

Figure 11. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2001. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

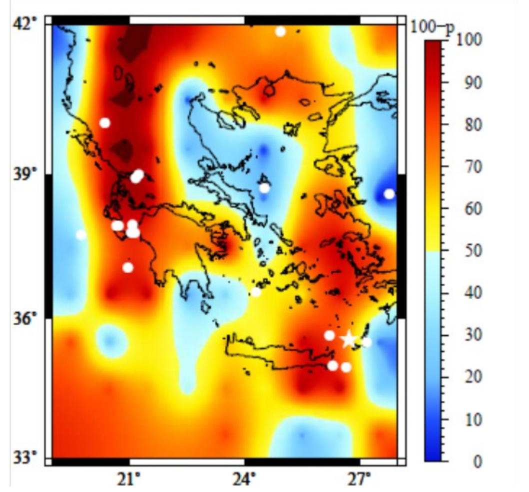

Figure 12. Compliance parameter p of the Lunar Monthly Synodic tidal period for the year 2002. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

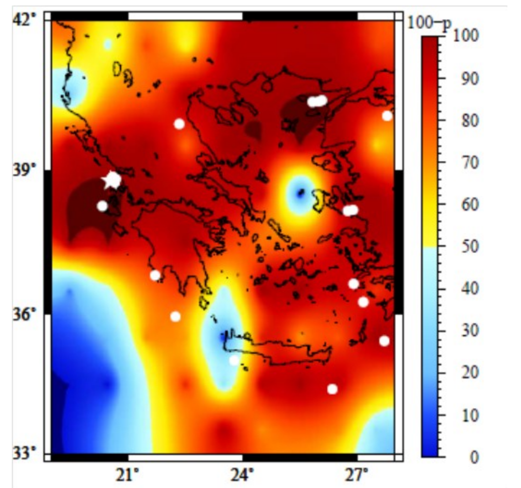

Figure 13. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2003. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

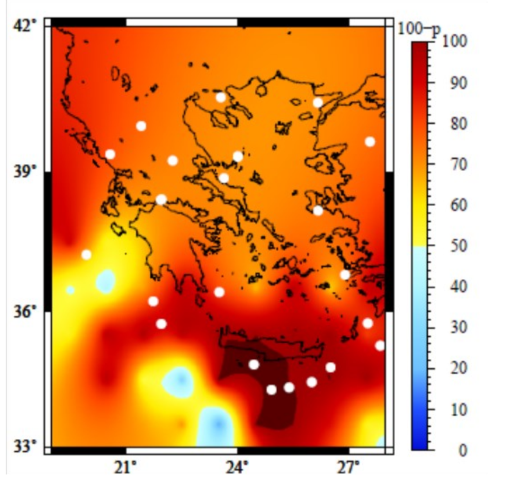

Figure 20. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2010. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

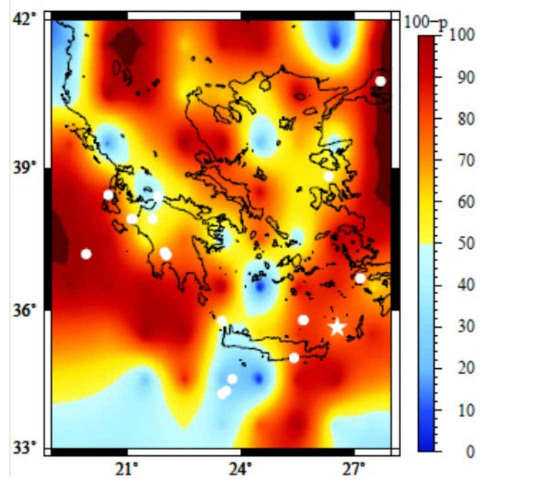

Figure 21. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2011. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

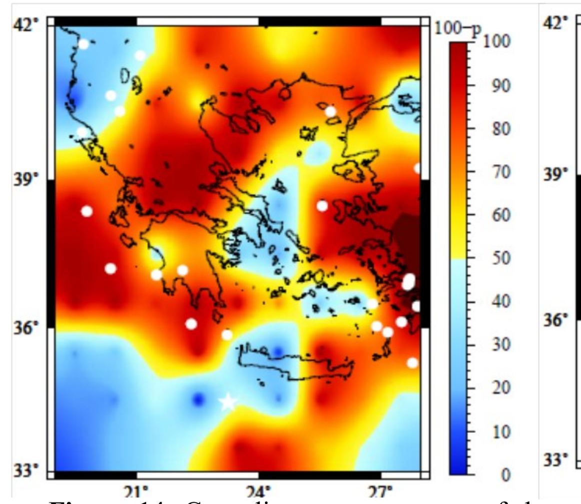

Figure 14. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2004. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

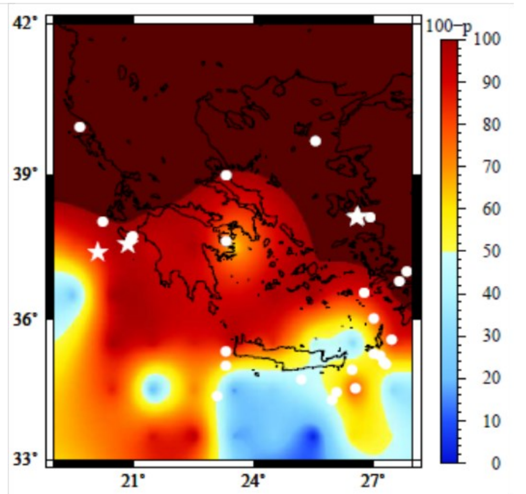

Figure 15. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2005. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

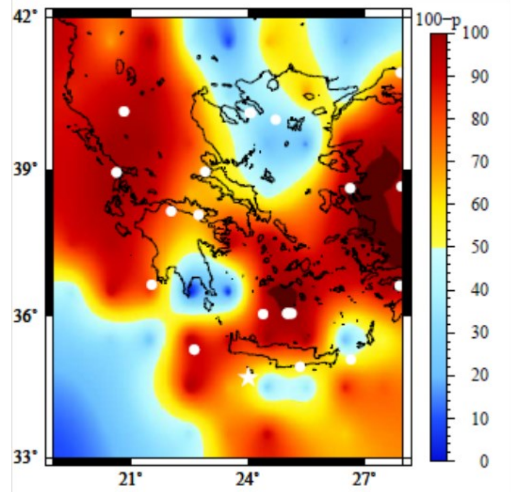

Figure 22. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2012. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

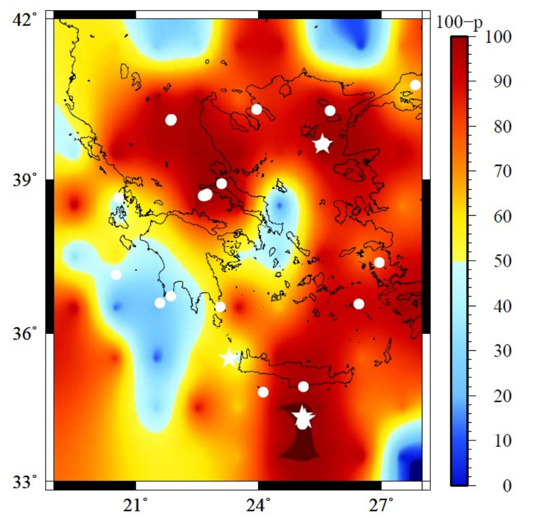

Figure 23. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2013. White marks indicate Earthquake

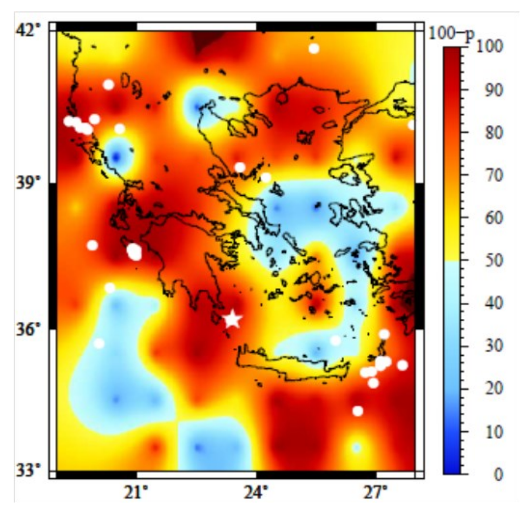

Figure 16. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2006. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

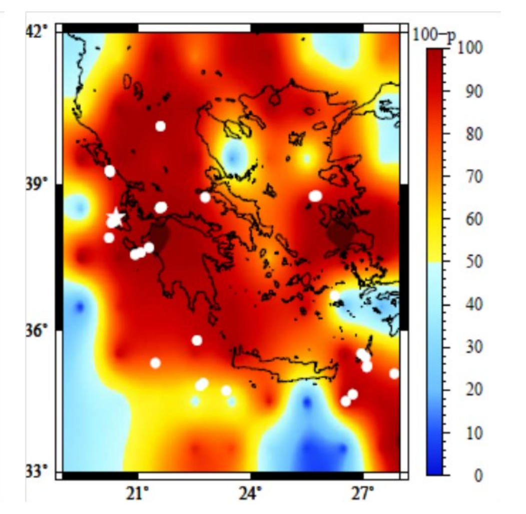

Figure 17. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2007. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

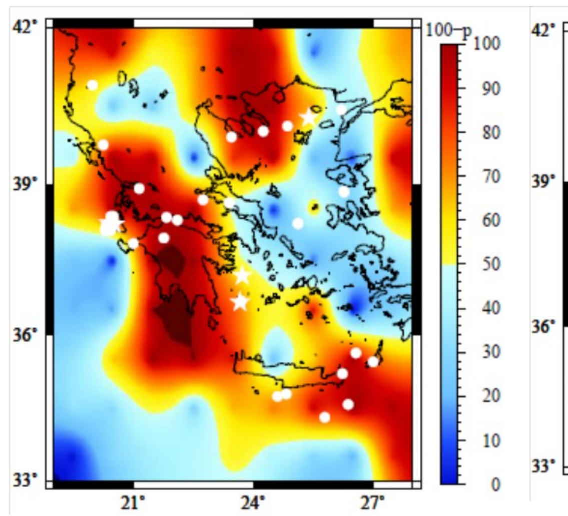

Figure 24. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2014. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

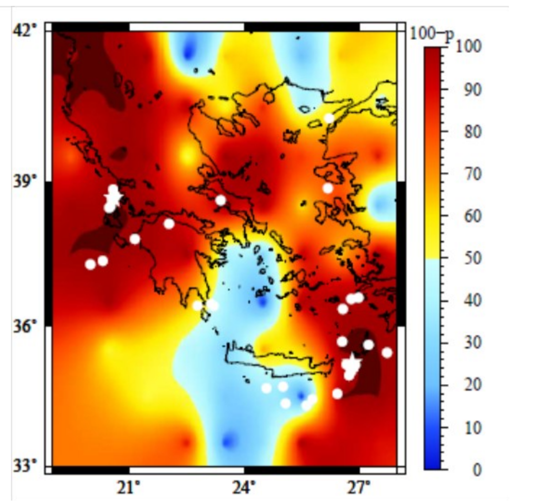

Figure 25. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2015. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

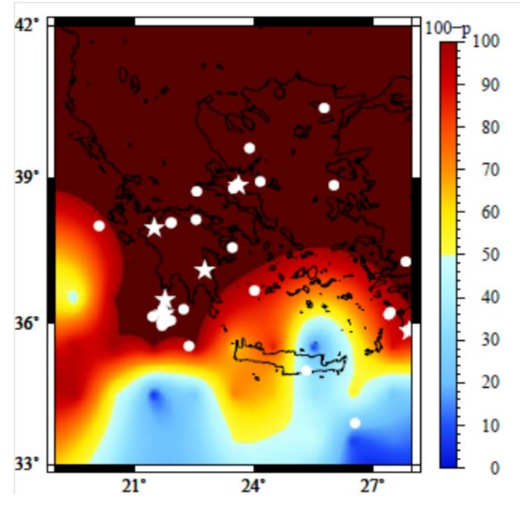

Figure 18. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2008. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

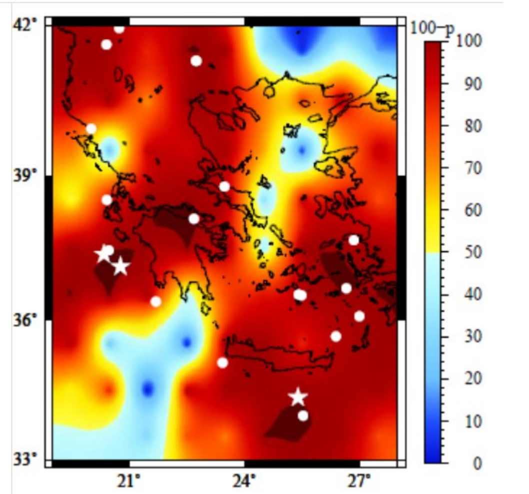

Figure 19. Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the year 2009. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M ≥ 5.5.

4. Concluding remarks

In this paper it is shown that the earth tide-seismicity *p* maps points to the broader area of pending strong earthquakes within a year with a confidence level of 99.7%. Thus we suggest that earth tide-seismicity *p* maps may be used for earthquake risk mitigation.

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