Variation of the Earth tide-seismicity compliance parameter the last 50 years for the seismic area of Evoikos, Greece

Contadakis, M.E.[1] , Arabelos D.N. [1], Vergos, G. [1],Spatalas, S. [1], Skeberis Ch.[2]

[1]Department of Geodesy and Surveying, University of Thessaloniki, Greece

[2] Department of Electrical & Computer Engineering, Aristotle University of Thessaloniki, Greece

Abstract

Abstract: Based on the results of our studies for the tidal triggering effect on the seismicity of the Hellenic area, we consider the confidence level of earthquake occurrence - tidal period accordance as an index of tectonic stress criticality for earthquake occurrence and we check if the recent increase in the seismic activity at the Evoikos Gulf indicate faulting maturity for a stronger earthquake. In this paper we present the results of this test which are positive.

Key words: Earthtides, Seismicity, Hi(stogram)Cum(ulation) method

1. Introduction

Applying the Hi(stogram)Cum(ulation) method, which was introduced recently 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) , (c) of the Hellenic Arc (Vergos et al. 2012) and (d) Santorini (Contadakis et al. 2013,Contadakis et al. 2014). The result of the analysis for all the areas indicate that the monthly variation of the frequencies of earthquake occurrence 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 frequency and tidal periods varies with seismic activity, i.e. the higher confidence level corresponds to 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. Based on these results, we consider the confidence level of earthquake occurrence - tidal period accordance, p, as an index of tectonic stress criticality for earthquake occurrence and we call it" **Earth tide-seismicity compliance parameter".** Then we check on posterior if the variation of the confidence level index, p, indicate the fault matureness in the case of the recent seismic activity at Fthiotida, Greece. In this paper we present the results of this test.

2. Seismicity in the broader area of Evoikos

On November of 17nth of 2014 a double earthquake of M_L=5.2 occurred in the area of North Central Evoikos, 25km North West of Chalkis, followed by a seismic activity with shocks of magnitudes weaker than 3.0 M_L. The area is a known tectonically quiet area in Greece, which shows an increasing microseismic activity since 1998 It should be noted that the main faults of the area are normal of NW-ES and W-E direction (Rondoyannis et al. 2007; Ganas et al. 2006) as it is shown in Figure 1.

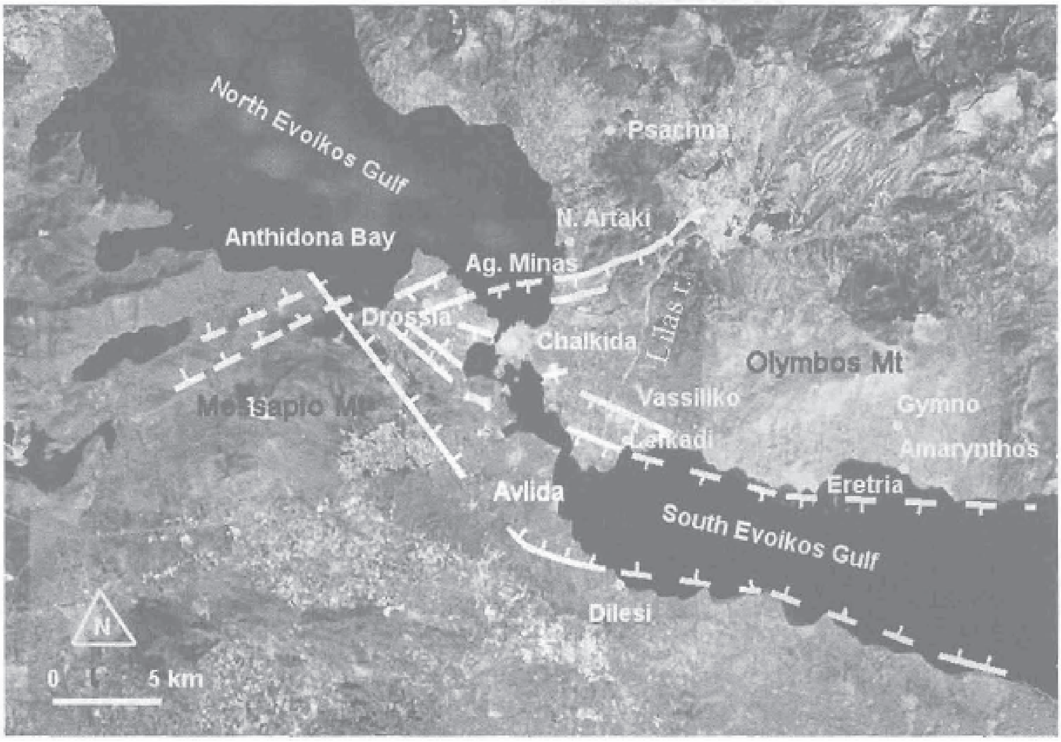

Figure 1. The Faulting of the South and Central Evoikos (Quoting from Rondoyannis et al. 2007).The locus of the seismic activity of 17 of November 2014 is at the upper left site of the picture.

In the broader area 12 Shallow earhquakes with 5.0<M_L<6.3 occurred during the last 50 years. Table 1 gives the characteristic parameters of these earthquakes.

Table 1. Eathquakes with M_L>5.0 occurred within the last 50 years in the area of Evoikos

Date of event	*hour(U.T)*	*φ(°)*	*λ(°)*	*Depth(km)*	M_L
1981 FEB 24	20 53 36.0	38.14	23.00	0	6.3
1981 FEB 25	2 35 50.0	38.20	23.00	0	5.9
1981 FEB 25	5 8 13.0	38.20	23.10	0	5.1
1981 MAR 4	21 58 4.0	38.30	23.20	0	5.8
1981 MAR 5	6 59 6.0	38.30	23.20	0	5.6
1981 MAR 7	11 34 42.0	38.20	23.30	0	5.1
1999 SEP 7	11 56 50.5	38.15	23.62	30	5.4
2008 OCT 14	2 6 34.7	38.85	23.62	24	5.6
2008 OCT 14	2 16 57.9	38.87	23.61	21	5.1
2010 MAR 9	2 55 0.9	38.87	23.65	22	5.1
2014 NOV 17	23 5 55.4	38.64	23.40	24	5.2
2014 NOV 17	23 9 3.2	38.64	23.41	23	5.2

For this area we apply the Hi(stogram)Cum(ulation) method , in order to see if Tidal triggering effect is been detected and if this effect is better traced in the period of the increased microseismicity i.e. the years 1998- 20th of November of 2014.

In our analysis we use the seismological data of the earthquake catalogue of NOA (http://www.gein.noa.gr). The set of data consist of a series of 5484 shallow and 92 of intermediate depth earthquakes with M_L ranging from 2 to 6.3 and occurred within the time interval from January1964 to 20 of November 2014, in an area bounded by $38.14^o \le \varphi \le 39.14^o$ and $23.00^o \le \lambda \le 23.28^o$. Figure 2 displaces the development of the seismicity in the area from 1964. It is seen that after an one year peak on 1981 the number of shocks per year start to increase from 1998 on and reaches a peak on 2010.

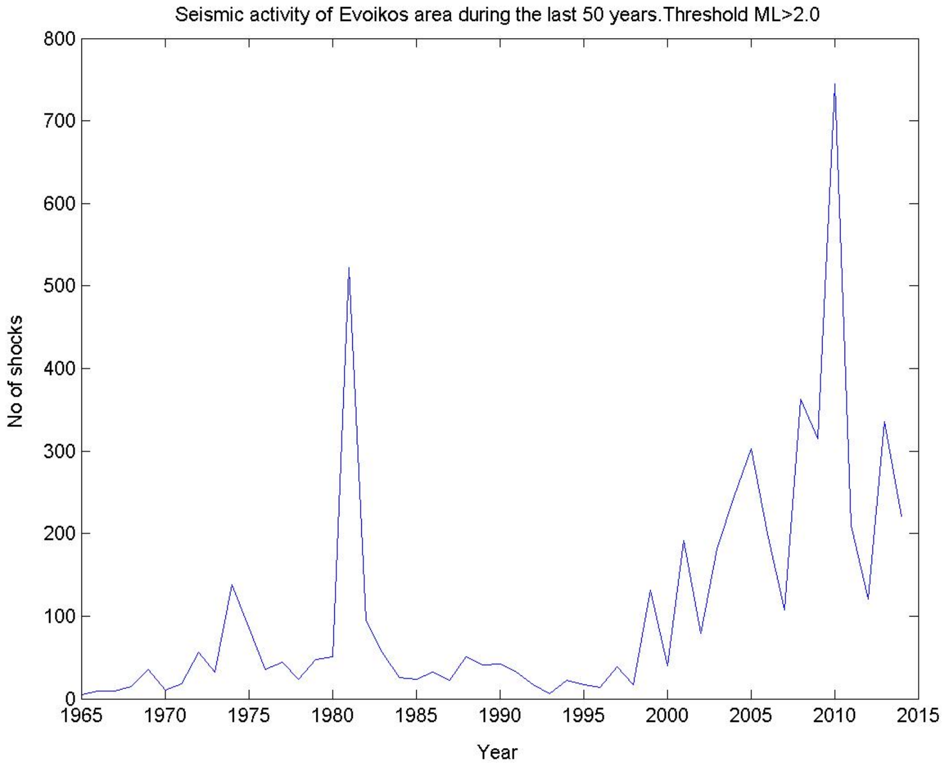

Figure 2. The development of the seismicity in the selected area from 1964 until 2014.

3. Tidal effect

Tidal effects on a rigid Earth can be computed theoretically from the ephemerides of the Moon, the Sun and the planets. The Earth tides are the combined effect of the mentioned celestial bodies and the reaction of the solid Earth (like an elastic body) to the tidal forces. The ocean tides follow the law of hydrodynamics, with strong disturbances affecting adjacent seas, so that the ocean loading effect has to be taken into account. Earth tides are discussed extensively in Melchior (1983), Baker (1984), Wilhelm et al. (1997), Torge (2001).

The constituents of the Earth tides for the area of Thessaloniki were determined gravimetrically by Arabelos (2002). Table 1 displays the strongest components of the Earth tides for Thessaloniki. Although the amplitude of the lunar tidal component M1 is equal 27.091 nms^{-2} (see Arabelos, 2002, Table 3), i.e. it is much weaker than the listed components, we consider in addition the possible effect of this constituent by means of the lunar synodic month (i.e. period from new moon to new moon which is $29^d.530589$) as well as by lunar anomalistic month (i.e. time period between two successive passages of the moon from perigee which is $27^d.554551$).

Table 3 displays the actual ocean corrected tidal parameters of O1 and M2 for Sofia, Instabul and Thessaloniki, and the corresponding values from the model of Wahr-Dehant-Zschau (Dehant 1987, Dehant and Zchau, 1989), expressing the dependency of the tidal parameters on the latitude. As it is shown from the table the amplitude factors of the principal O1 and M2 tidal constituents agree within their error of estimation with the model.

Table 3. The strongest components of Earth tides in Thessaloniki

Symbol	Period T(min)	Signal/ noise	Amplitude (nms^{-2})	Origin
K1	1436	525.1	487.840	Lunar & Solar declination wave
O1	1549	379.7	352.816	Lunar principal wave
M2	745	1208.5	510.350	Lunar principal wave
S2	720	564.5	238.393	Solar principal wave

For the latitude of 38^o which is the mean latitude of the area under consideration, the extrapolated model amplitude factors for O1 and M2 are equal to 1.156 and 1.158 respectively. Consequently, the amplitudes of O1 and M2 might be changed to about 408 and 591 nms^{-2} respectively, which are very close to the amplitudes observed in the tidal station of Thessaloniki. However, this estimation does not take into account the actual elastic properties of the lithosphere in the Ionian zone.

Table4. Ocean corrected parameters of O1 and M2 in 3 neighboring stations

	Sofia (latitude=42.71^o)		Istanbul (latitude=41.07^o)		Thessaloniki (latitude=40.63^o)	
	Amplitude factor	Phase degree	Amplitude factor	Phase degree	Amplitude nm factor	Phase degree
O1	1.1493±0.0014	-.1590±.060	1.1564±0.0035	-.281±0.174	1.1536±0.003	-.201±0.151
Model	1.1540	-0.2	1.1542	-0.2	1.1543	-0.2
M2	1.1541±0.0005	-.207±0.026	1.1587±0.0011	-.039±0.026	1.1639±0.001	-.195±0.001
Model	1.1541	-0.2	1.1583	-0.2	1.1583	-0.2

4. Method of Analysis

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:

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

where ϕ_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^o 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.

A crucial point of this analysis is the use of a proper statistical test which will give us arguments to decide if such a result is correct or not i.e. will provide us a proper confidence level to our decision. To this purpose 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:

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

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.

5. Results

Figures 3 to 8 display the Cumulative Histogram for all the 221 earthquakes which occurred in the time interval from January 1st, 2014 to 20^{th} of November, 2014, and correspond to the tidal periods of Anomalistic Monthly period(i.e. time period between two successive passages of the moon from perigee which is $27^d.554551$) (Figure 3), Synodic Monthy period (i.e. period from new moon to new moon which is $29^d.530589$) (Figure 4), Diurnal luni-solar constituents K1 (Figure 5), Diurnal luni-solar constituent O1(Figure 6), Semi-diurnal solar constituents S2 (Figure 7), and Semi-diurnal lunar constituent (Figures 8), for the last year of the 50-year analyzed data, i.e. 2014. It is obvious that there is a perfect compliance of tidal and earthquake frequency distribution for all the Tidal constituent. Monthly Anomalistic and Synodic periods, the Semi-diurnal solar S2 periods and Diurnal luni-solar O1 as well as the Semidiurnal lunar period are in 200 degrees phase lag while the Diurnal luni-solar K1 is in phase with respect to the corresponding tidal variation. This perfect compliance is shown in Table 5. This table displays the corresponding confidence levels for all six tidal components for 2014 together with the same quantities for a year of low tectonic activity, i.e. 1994 and the mean confidence levels for the 50 years.

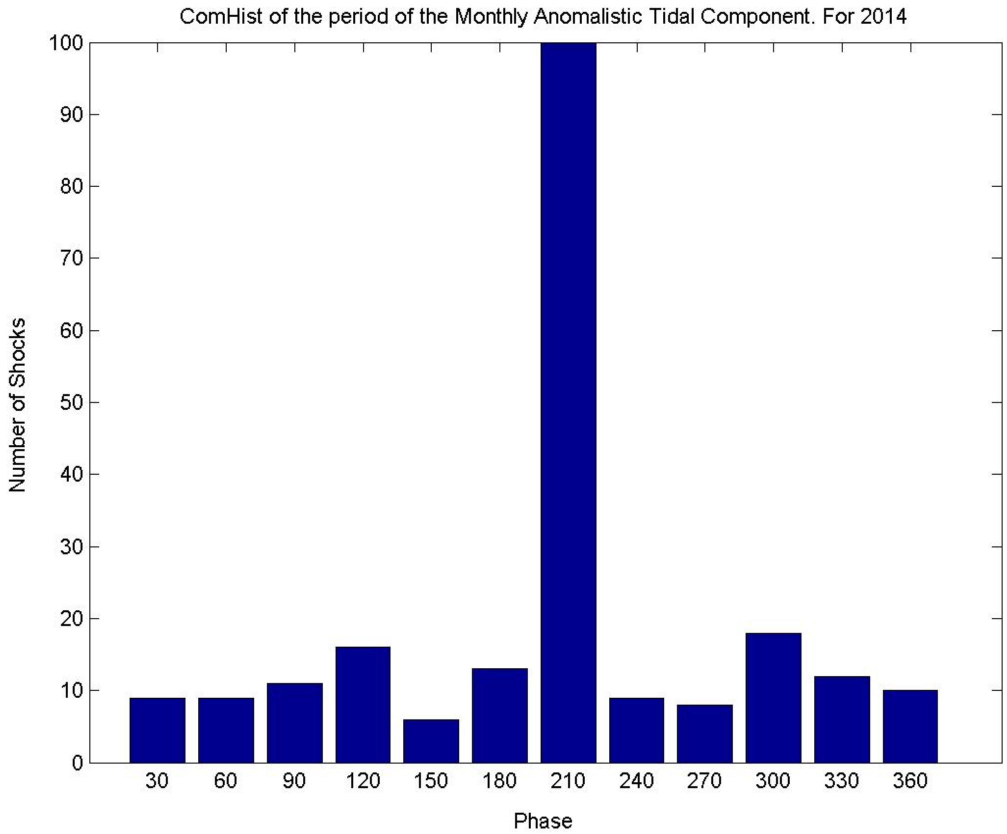

Figure 3. Cumulation Histogram for the Anomalistic Monthly period for 2014

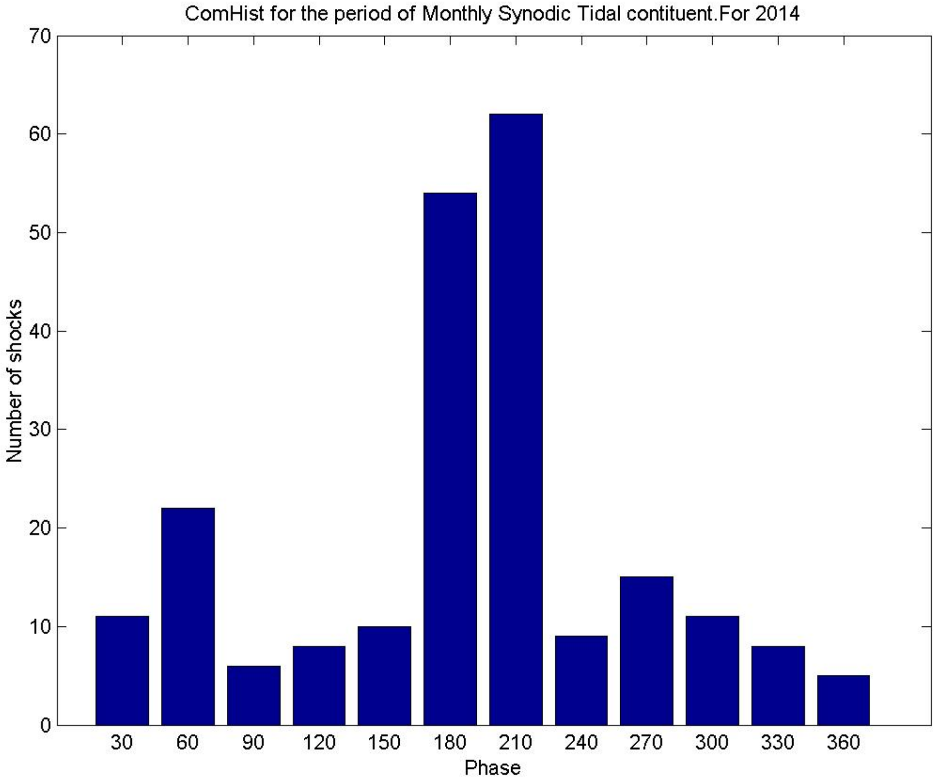

Figure 4. Cumulation Histogram for the Synodic Monthly period for 2014

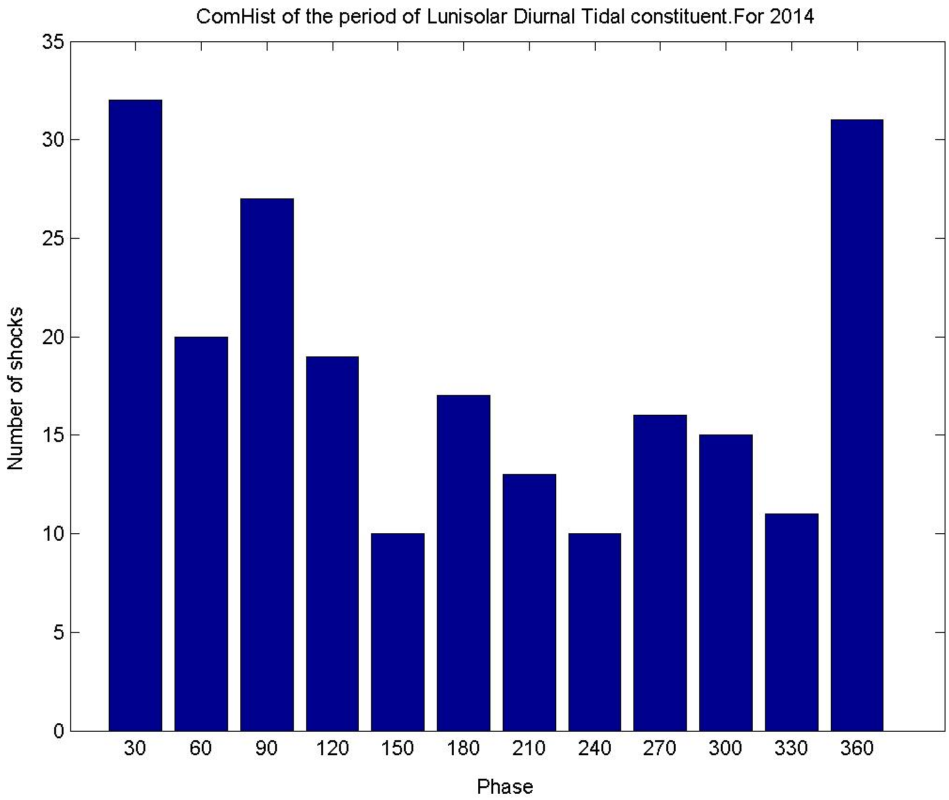

Figure 5. Cumulation Histogram for the Luni-Solar K1 period for 2014

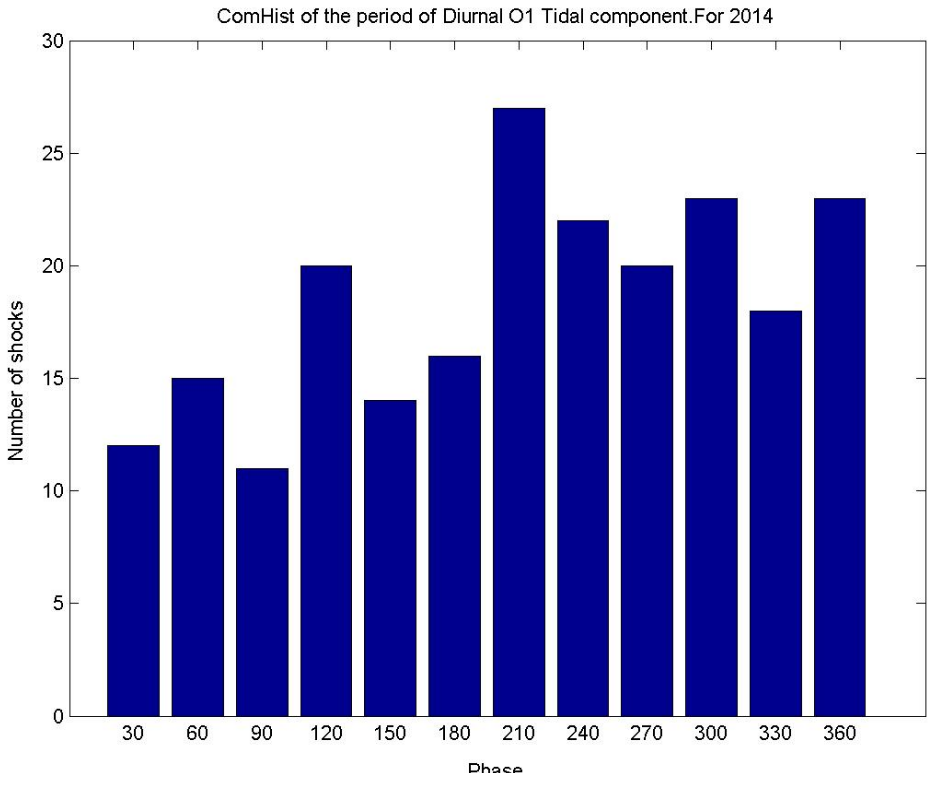

Figure 6. Cumulation Histogram for the Luni-Solar O1 period for 2014

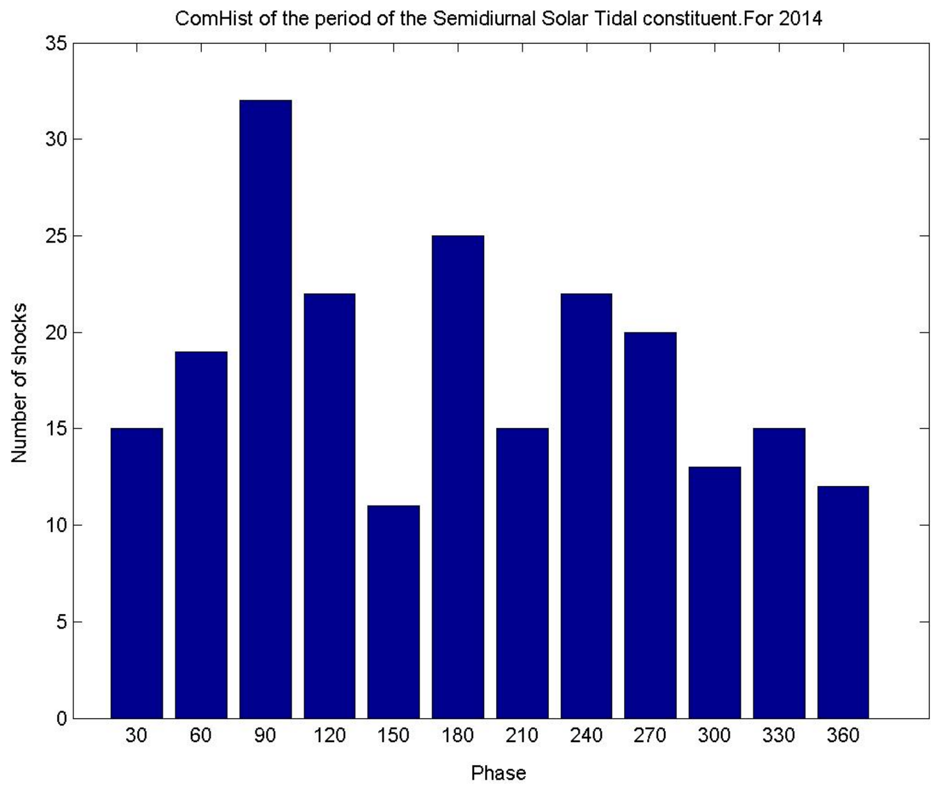

Figure 7. Cumulation Histogram for the semi diurnal Solar S2 period for 2014

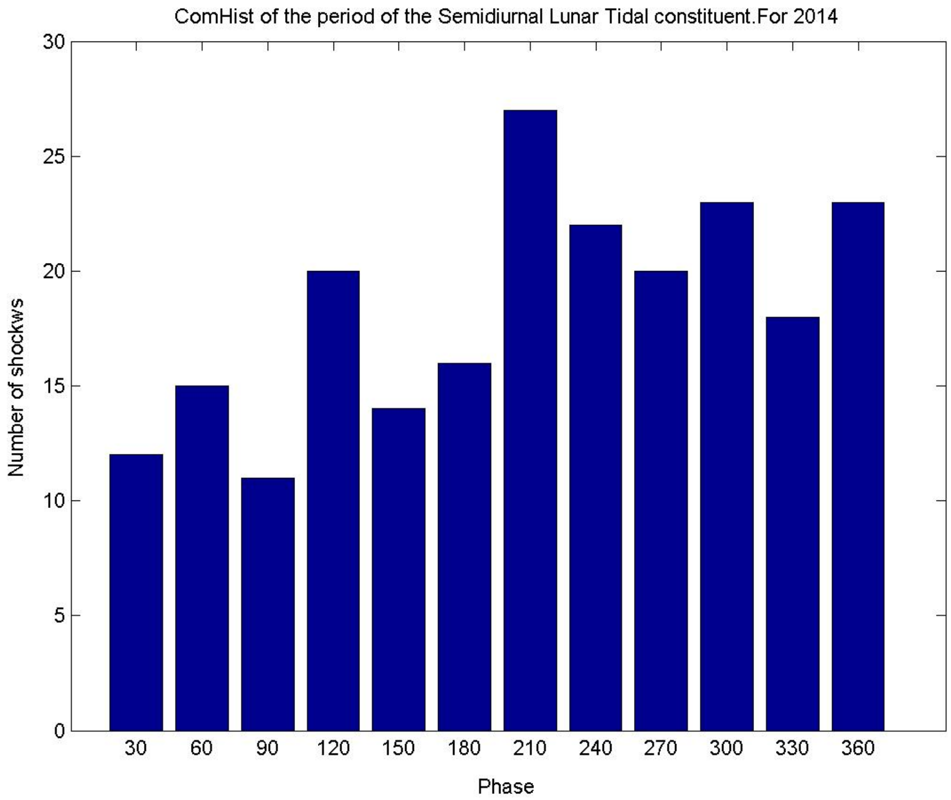

Figure 8. Cumulation Histogram for the semi diurnal Lunar M2 period for 2014

Table 5. The confidence level of earthquake-Earth tide correlation for all the earthquakes of Evoikosw area for 2014 in comparison with Mean and those of 1994

	MAnom.	MSynod	K1	O1	S2	M2
Mean	0.24166	0.27108	0.47115	0.36711	0.406794	0.407274
1994	0.9306	0.7175	0.0047	0.9135	0.7084	0.43849
2014	0.0009	0.0000	0.0000	0.0923	0.1609	0.0189

Table 5 indicates also that the confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area. This is shown also in figures 9 to 14. These figures display the variation of the confidence level parameter in the time period 1964 to 2914 together with the earthquakes frequency for each year for all six periods. Arrows indicate the occurrence of strong earthquakes (M_L>5.0) while double earthquakes are marked with one arrow.The high compliance for the monthly tidal components, despite their small intensity may indicate that they provide in general favorable conditions for the action of the much stronger tidal components K1 and M2. In this point we may refer to the fact that the monthly tidal barometric variations are quite sensitive to the seismic activity (Arabelos et al. 2008). Perhaps this peculiar coincidence merits further investigation.

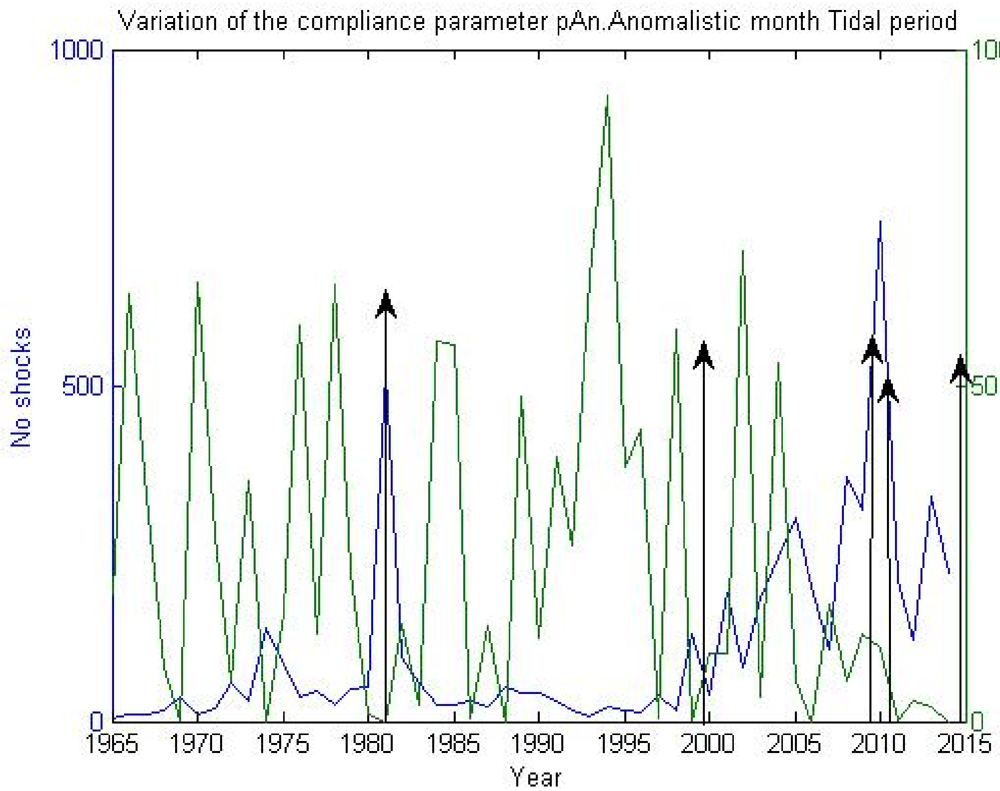

Figure 9. The confidence level parameter p between Seismicity and Tidal Anomalistic Monthly period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964

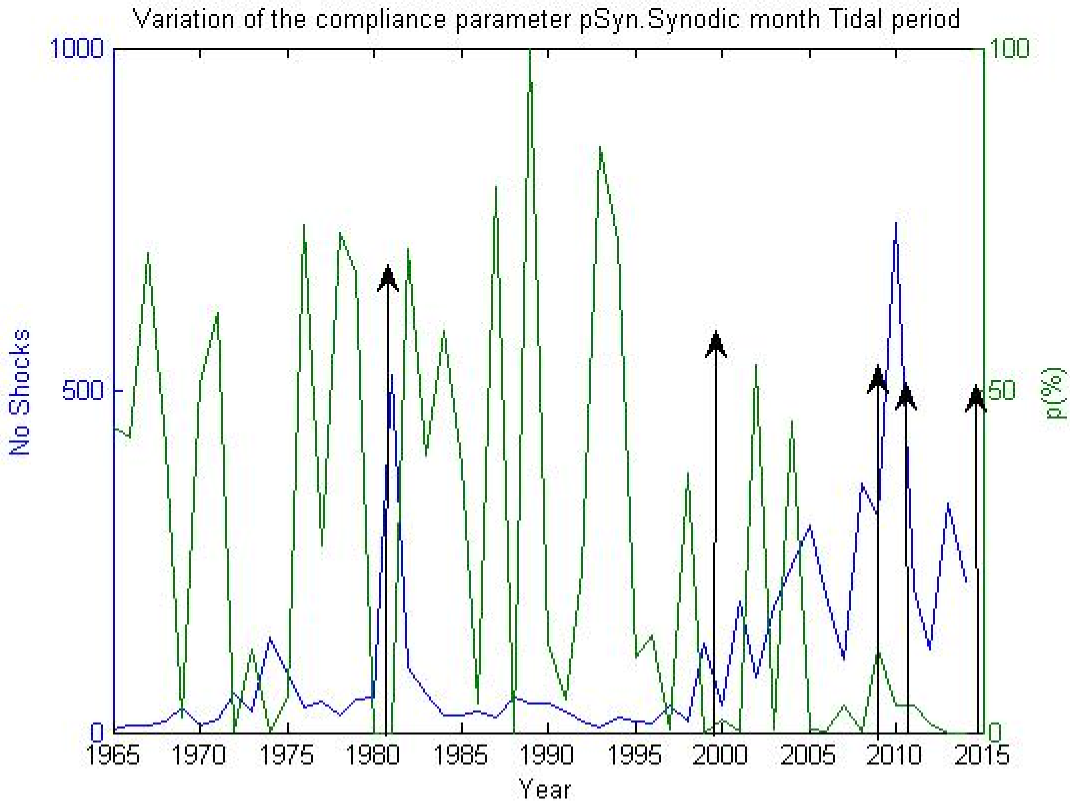

Figure 10. The confidence level parameter p between Seismicity and Tidal Synodic Monthly period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964

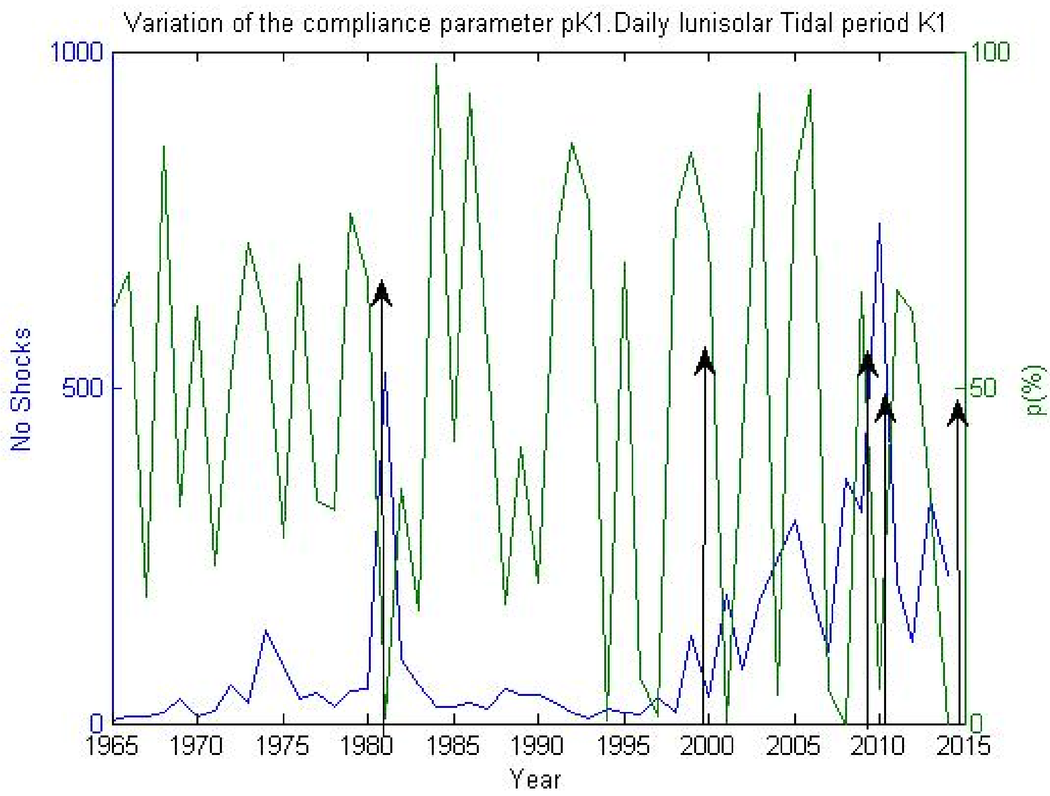

Figure 11. The confidence level parameter p between Seismicity and diurnalTidal Luni-Solar K1 period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964

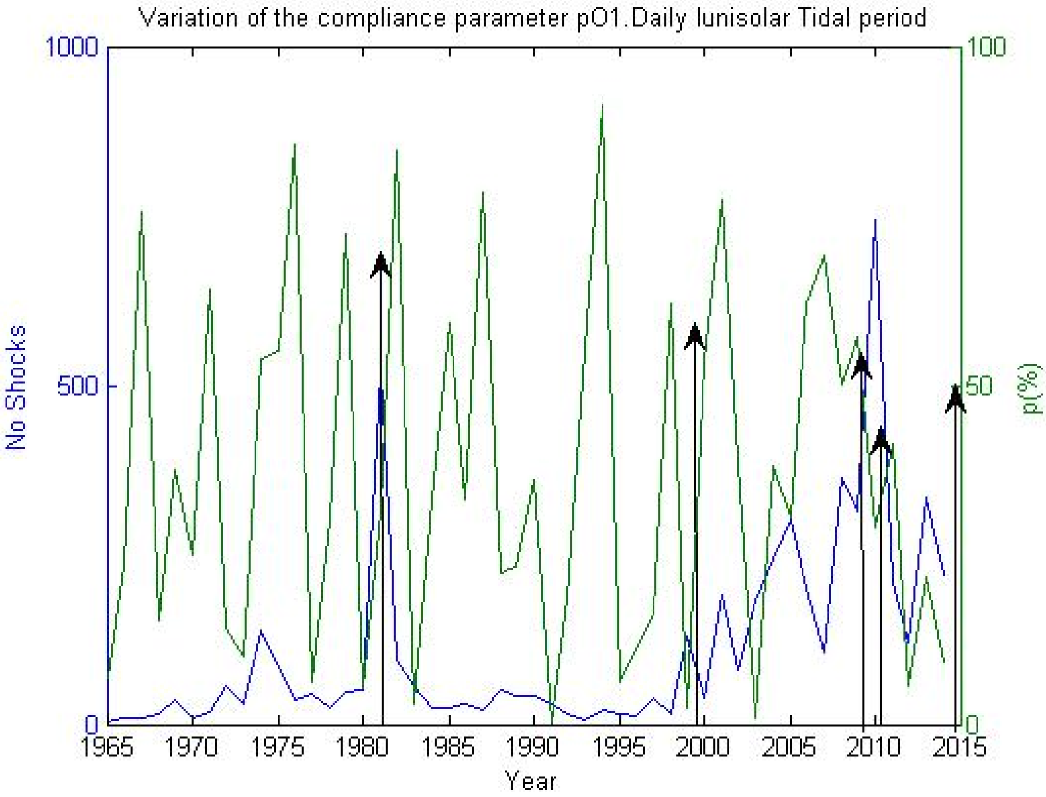

Figure 12. The confidence level parameter p between Seismicity and Tidal diurnal Luni-Solar O1 period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964

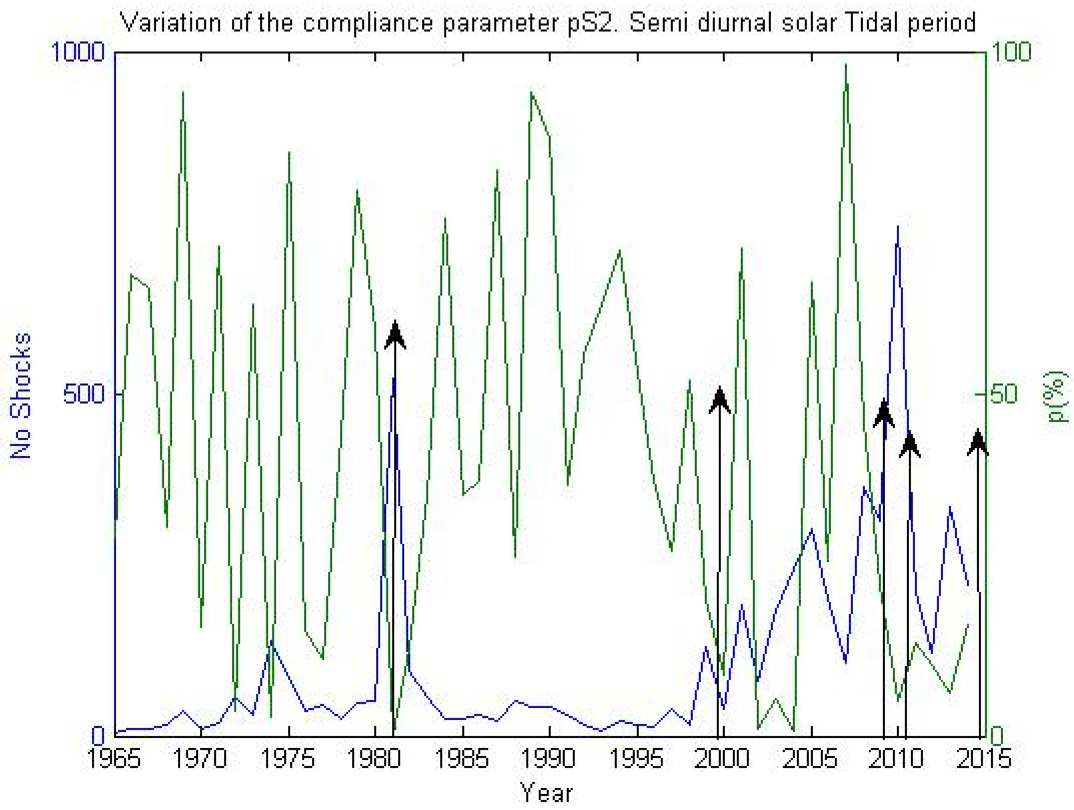

Figure 13. The confidence level parameter p between Seismicity and Tidal semi diurnal Solar S2 period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964

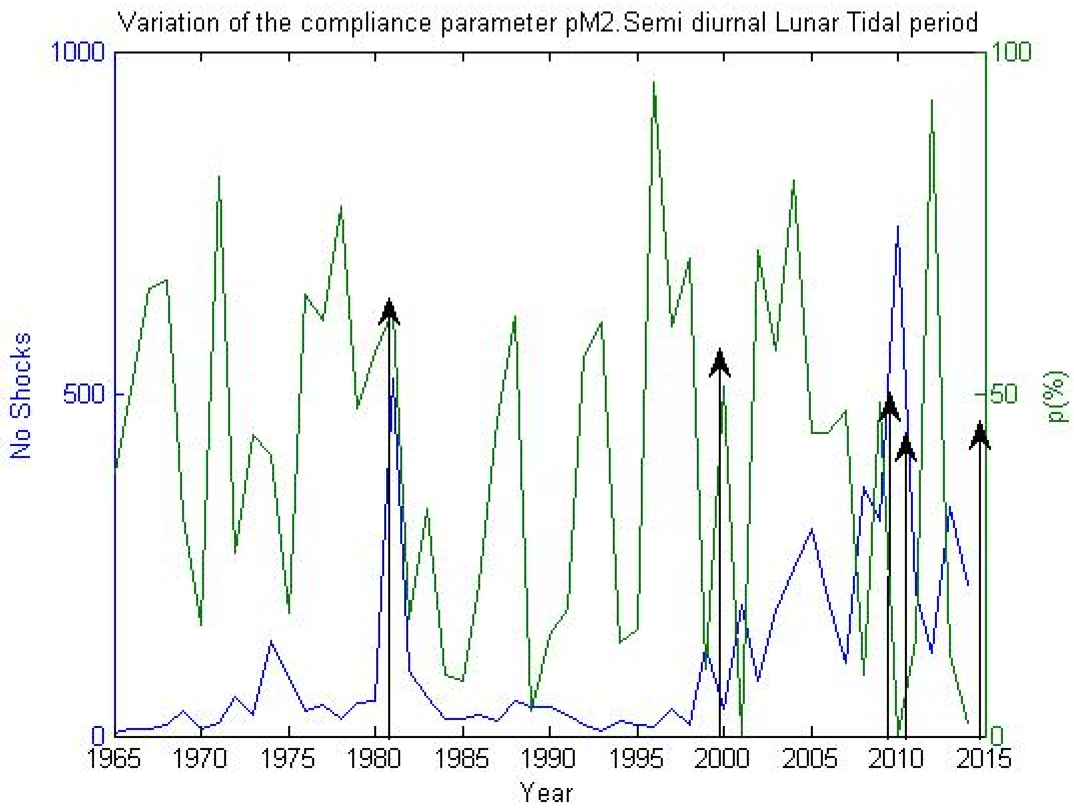

Figure 14. The confidence level parameter p between Seismicity and Tidal semi diurnal Lunar M2 period. Arrows indicate the earthquakes with M_L >5.0 at Evoikos since 1964.

6. Conclusions

In this paper we investigate the tidal triggering evidence on the earthquakes of the area of Evoikos Gulf in Greece. The result of our analysis using the HiCum method, indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly (Mm) variations. The same happens with the corresponding diurnal and semi-diurnal variations of the frequencies of earthquake occurrence with the diurnal (K1),(O1) and semi-diurnal solar (S2) and semidiurnal lunar (M2) tidal variations. The confidence level of the Tidal-Earthquake frequency period compliance is very sensitive to the seismicity of the area and we call it Tidal -Earthquake frequency compliance parameter. We suggest that this parameter may be used in earthquake risk evaluation.

References

Arabelos, D., 2002 Comparison of Earth-tide parameters over a large latitude difference Geophys. J. Int. (Research Note), 151, 950-956

Arabelos, D.N., Asteriadis G., Bloutsos A., Contadakis M.E., Spatalas S. D.(2008). Correlation between seismisity and barometric tidal exalting, Nat. Hazards Earth Syst. Sci., Vol 8, 1129-1137

Baker, T.F. ,1984, Tidal determination of the Earth, Sci. Progr., Oxford 69: 197-233

Cadicheanu, N., van Ruymbeke, M and Zhu P.,2007: Tidal triggering evidence of intermediate depth earthquakes in Vrancea zone(Romania), *NHESS 7,733-740*

Contadakis, M. E., Arabelos, D. N., Spatalas, S., 2009, Evidence for tidal triggering on the shallow earthquakes of the seismic area of Mygdonia basin, North Greece, in Terrestrial and Stellar Environment, eds.D. Arabelos, M.E.Contadakis, C.Kaltsikis,I.Tziavos,Ziti Press Thessaloniki,Greece,pp 223-235

Contadakis, M. E.,Arabelos, D.N., Spatalas, S.D., 2012, Evidence for tidal triggering for the earthquakes of the Ionian geological zone, Greece, *Annals of Geophysics,* Vol. 55, No. 1, p. 73-81

Contadakis, Michael E.; Arabelos, Dimitrios N.; Vergos, George, 2013,Testing the recent Santorini seismic activity for possible tidal triggering effect, GA . EGU2013-8358

Contadakis, M.E,Arabelos, D.N.,Vergos, G.,Spatalas, S.D.,2014, Variation of the Earth tide-seismicity compliance parameter during the recent seismic activity of Fthiotida, Greece, EGU General Assembly 2014, 1121

Dehant, V., 1987, Tidal parameters for the inelastic Earth, Phys. Earth Planet Inter., 49, 97-116.

Dehant, V. and Zschau, J. ,1989, The effect of mantle inelasticity on tidal gravity: a comparison between the spherical and the elliptical Earth model. Geophys. J., 97, 549-555

Ganas A., Sokos E., Agalos A., Leontakianakos G. ,Pavlides S., 2006, Coulomb stress triggering of earthquakes along the Atalanti Fault, central Greece: Two April 1894 M6+ events and stress change patterns, Tectonophysics ,420, 357–369

Melchior, P. ,1983, The Tides of the Planet Eath, Pergamon Press, New York

Rondoyanni,Th.,Galanakis, D.,Georgiou,Ch., and Baskoutas I., 2007, Identifying fault activity in Central Evoikos Gulf (Greece), Bulletin of the Geological Society of Greece Vol XXXX,2007,Proceedings of the 11th International Congress,Athens May of 2007

Schuster, A. ,1897, On lunar and solar periodicities of earthquakes, Proc. R.Soc. Lond., 61, 455-465

Tanaka, S., Ohtake, M., and Sato, H. , 2002, Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data. J. Geophys. Res., 107(5B10), 2211.

Tanaka, S., Sato, Matsumura, S., and H.,Ohtake, M. ,2006, Tidal triggering of earthquakes in the subducting Philipine Sea plate beneath the locked zone of the plate interface in Tokai region, Japan. Tectonopysics, 417, 69-80

Torge, W., 2001, Geodesy, 3rd Edition, Walter de Gruyter, Berlin-New York

Vergos, G., Arabelos, D. N., Contadakis, M. E., 2012, Evidence for Tidal triggering on the earthquakes of the Hellenic Arc, Greece.,Geoph.Res.Abs,Vol 14,2325