Chapter 2

# Correlation between Seismic and Volcanic Activity at a Large Spatial Scale in Italy: Examples from the Neapolitan Volcanic District (Vesuvius Volcano, Southern Italy)

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Additional information is available at the end of the chapter

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**Abstract**

The time correlation between the eruptions of Mt Vesuvius and the occurrence of strong earthquakes in Italy has been revised using new and improved catalogs and data made available in the last decade. It has been shown that this correlation is statistically significant and involves also the earthquakes located very far from the volcanic edifice (hundreds of kilometers). In particular, the earthquakes and the Vesuvius' eruptions agree on a transient of accelerated activity between 1600 and 1900. A similar correlation has been found between the seismicity and the uplift episodes at the nearby Campi Flegrei caldera occurred in the last 70 years: there is strict similarity between the two cycles, the first one centered around 1970–1980 and the second one started on 2004 and still continuing and involving recent strong earthquakes (2009 L'Aquila earthquake, 2012 Emilia earthquake and 2016 Central Italy earthquake). The synchronization to such a long distance has suggested the occurrence of large-scale climatic processes controlling both the earthquakes and the volcanism. The comparison with climatic indexes like the global surface temperature and the extension of glaciers in western-central Europe has indicated a possible role of climatic parameters in controlling volcanism and seismicity.

**Keywords:** Mt Vesuvius, Campi Flegrei caldera, Italian seismicity, event synchronization, Ripley's K-function

## 1. Introduction

The correlation between the volcanic activity and the earthquakes is a well-known subject of investigation. It commonly refers to two distinct aspects: first, the seismicity in volcanic areas related to magmatic and hydrothermal movements, which is of interest for predicting the possible volcano unrest [1] and second, discussed in this chapter, the possible triggering of eruptions caused by stress transfer due to strong earthquakes, even located far from the volcano edifice [2]. A recent study carried out to a global scale [3] has shown that this mechanism of triggering is effective for very strong earthquakes (Mw ≥ 7.5) located within 200 km from the volcano. In Italy, the availability of reliable catalogs covering several centuries of earthquake and eruptive observations gives the possibility to explore the long-distance volcanic/seismic relationship with more detail. According to previous studies [4–6], such link is particularly evident for the eruptions of Mt Vesuvius, near Naples, in southern Italy (triangle in **Figure 1**).

The Vesuvius volcano is one of the most studied in the world. Through the centuries, eruptions were described by Neapolitan and foreign scholars. A significant step was performed on 1841, with the institution of the "Osservatorio Vesuviano", the first volcanology observatory in the world. Nowadays, Mt Vesuvius is monitored by a dense network of seismic, geochemical, and GPS stations (http://www.ov.ingv.it/ov/it/vesuvio). Its eruptive history for the last 2000 years is well known through the historical sources and the archaeomagnetic dating of

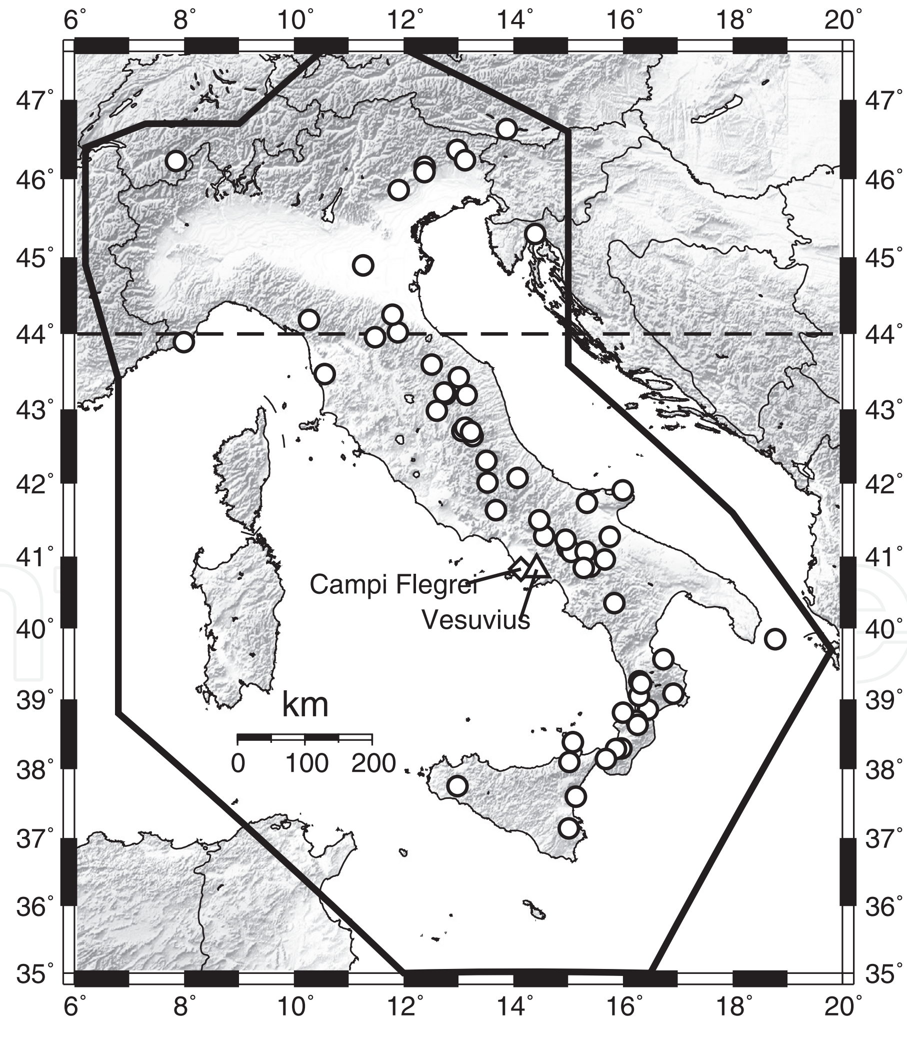


**Figure 1.** Epicenters of Mw ≥ 6.0 earthquakes occurred in Italy between 1600 and 2016 (declustered catalog).

volcanic deposits [7]. In particular, in the last millennium, after a few centuries of weak activity, the Vesuvius awakened on 1631 and entered in a long period of sustained and almost continuous activity concluded with its last eruption of 1944 [8], followed by the current phase of quiescence.

In the last few decades, geological and geophysical investigations have improved the knowledge about the tectonic setting of Mt Vesuvius as well as its internal structure and magmatic system [4, 9, 10]. Concerning the relationships with far seismicity, [4] has furnished statistical evidence for the time correlation between the eruptions of Mt Vesuvius and moderate-strong earthquakes (Mw ≥ 5.4) in the Southern Apennines. In [5], such correlation is modeled as the effect of mutual stress transfer working at distances up to 150 km. In [6], it has been observed that the synchronization of eruptions with Mw ≥ 6 earthquakes occurring throughout the national territory, even hundreds of kilometers far from the volcano and in different tectonic domains. This finding has suggested the occurrence of a common cause at the basis of the two phenomena rather than a direct interaction or mutual triggering.

The investigation of the seismic/volcanic relationship requires two components: statistical methods to assess the existence of the correlation and to estimate its strength and geophysical methods able to furnish realistic models for its occurrence. This chapter is focused on the first aspect and presents an application of the modified Ripley's K-function to countrywide strong seismicity and to the eruptions of Mt Vesuvius since the seventeenth century.

Statistics alone is not able to distinguish between a causal relationship (earthquake triggering eruptions) and the co-causal hypothesis (an external mechanism controlling both earthquakes and eruptions). Elements on this topic can be obtained looking at the bradyseism of the Campi Flegrei caldera (white diamond in **Figure 1**). The caldera and Mt Vesuvius are very near (25 km apart), share a similar regional tectonic environment, and, according to [11], have a common magma chamber. Furthermore, they alternate over time: the caldera was at rest during the intense eruptive period of Mt Vesuvius (1631–1944) and reactivated with an uplift process just after its conclusion (around 1950). Similarly to the eruptions of Mt Vesuvius, the phases of major uplift coincide with accelerated seismic activity in Italy. In a way, the two volcanoes look like twin systems with related behavior. The hypothesis here assumed is that what observed for the sismic/volcanic connection at Campi Flegrei in the last few decades can be reasonably extended to the past activity of Mt Vesuvius. In respect to analyzing rare eruptions, the bradyseism offers more details, thanks to the density of uplift measures in the last 70 years (almost continuous since 2000).

Recent works [6, 12, 13] have pointed out the correspondence between variations in the rate of seismicity throughout Italy and the climatic changes of the last millennium. In particular, the seismic activity accelerated during the most severe period of the Little Ice Age (between 1600 and 1900), while it seems to decrease in the current phase of global warming.

At the end of this chapter, it will be shown that this correspondence can be extended to the eruptive history of Mt Vesuvius. The finding leads to the hypothesis that the climate-related surface processes like glaciation/deglaciation and sea level changes could play a significant role in regulating both the eruptions and the earthquakes.

## 2. Volcanological and seismological data

The eruptive history of Mt Vesuvius is drawn from the Smithsonian's Global Volcanism Program (GVP) database ([14]; http://www.volcano.si.edu), where each eruption is described by its start date, by its end date, and by the Volcanic Explosivity Index (VEI [15]). An eruption can last from days to decades, and the VEI is attributed based on the strongest, often final, episode. The current analysis has been performed for the eruptions with VEI ≥ 2, assuming that for Mt Vesuvius, the catalog is complete at this level since the year 1600. This is a work hypothesis that seems to be acceptable given the proximity of the volcano to Naples, one of the largest cities in Europe since the Middle Ages. The selected dataset includes 25 eruptions since 1631. The last eruptive cycle started on 1913 and concluded on 1944 (VEI = 3).

The earthquake catalog herein adopted is the same of [13]. Its main characteristics and the processing steps are summarized as it follows. For the years between 1600 and 2014, the seismic events are drawn from the latest revision of the "Catalogo Parametrico dei Terremoti Italiani" (CPTI15, release 1.5 [16]). The dataset extends up to the end of 2016 with the earthquakes reported in the European-Mediterranean Regional Centroid Moment Tensor (RCMT) Catalog [17]. The resulting catalog includes the earthquakes located in Italy and in a narrow surrounding area. Among these events, only the mainshocks have been considered: the clusters of aftershocks have been removed using the algorithm described in [18]. It is important to guarantee that the catalog is complete at the same magnitude level in different time periods to avoid a biased analysis. To this purpose, after considering the completeness analysis carried out in [19], the catalog is assumed to be complete for a moment magnitude Mw larger or equal to 6. The selected dataset contains 60 earthquakes, including the recent destructive earthquake of Central Italy, occurred on August 24, 2016 (Mw 6.2 [17]).

A correlation analysis has been performed for the vertical ground movements at Campi Flegrei. A time history for the period 1905–2017 has been obtained merging the geodetic measurements available from 1905 to 2009 for the benchmark 25A in a leveling line established by the Istituto Geografico Militare (IGM) on 1905 [20], the measurements collected between January 2000 and July 2013 at the GPS station RITE located about 200 m from the benchmark 25A [21], and more recent GPS measurements from the same station (August 2014–April 2017) published in the online monthly bulletins published by the Osservatorio Vesuviano (http://www.ov.ingv.it/ov/campi-flegrei).

## 3. Time correlation between the eruptions of Mt Vesuvius and strong earthquakes throughout Italy

In this section, the times of occurrence of Vesuvius' eruptions, $V = \{V_1, \ldots, V_{nV}\}$, and those of strong earthquakes in Italy, $E = \{E_1, \ldots, E_{nE}\}$ are compared to assess their time correlation. There are different techniques to perform the task. One possibility, if the number of events sufficiently large, is to compare the histograms representing the time distribution of the events: the period of observation ($t_{start}$, $t_{end}$) is subdivided in $n_b$ bins of equal width $\Delta t$ and the analysis is performed for the two time series $X = \{X_1, \ldots, X_{nb}\}$ and $Y = \{Y_1, \ldots, Y_{nb}\}$, where $X_i$ and $Y_i$ are the number of eruptions and earthquakes in the *i*th time bin, respectively. The degree of correlation can be assessed parametrically, using Pearson correlation, which assumes a bivariate normal distribution of data, or non-parametrically, using either Kendall or Spearman rank correlation, which are independent on the type of data distribution. A more flexible way to represent and compare two time distributions of events (useful even in the case they are rare) looks at their smoothed time density obtained by Gaussian kernel estimation [22]. The correlation coefficient (Pearson, Kendall or Spearman) is computed for the two functions

$$\hat{f}(t) = \frac{1}{n_V}\sum_{i=1}^{n_V}\varphi(V_i - t; h)\ \hat{g}(t) = \frac{1}{n_E}\sum_{i=1}^{n_E}\varphi(E_i - t; h) \tag{1}$$

where $\varphi(z;h)$ is the kernel function (zero-mean normal density function in $z$ with standard deviation $h$), and $h$ is the smoothing parameter (the larger $h$, the larger the degree of smoothing). Both approaches suffer a common limitation: their results depend on the time resolution adopted for the analysis (i.e., the width of the bin for the histogram, the smoothing parameter for kernel density estimation). In general, a large time window could lead to similar flat distributions and then to a spurious high correlation. A partial solution is to perform a sensitivity analysis, checking how the value of the correlation coefficient varies for different time resolutions. A totally different approach is that based on the bivariate, Ripley's K-function [23] simplified for one dimension [24, 25]. It works directly on the two sets of event times, avoiding any transformation and arbitrary choice of parameters and consequent loss of information. The K-function is a function of time with equation.

$$K_{\mathrm{VE}}(t) = \frac{T}{n_V n_E}\sum_{i=1}^{n_V}\sum_{j=1}^{n_e} I\left(\left|V_i - E_j\right| < t\right), \tag{2}$$

where $I()$ is the identity function (it returns 1 if its argument is true, 0 otherwise) and $T$ is the total period of observation in years. The $K$-function is transformed to obtain the $L$-function

$$L_{\mathrm{VE}}(t) = \frac{K_{\mathrm{VE}}(t)}{2} - t \tag{3}$$

The L-function is associated with a 95% confidence envelope computed using $N$ randomizations of $V$ and $E$ (N = 1000 in the present analysis). If, for given t, $L_{VE}(t)$ is larger than the confidence envelope, then the number of couples for which $|V_i - E_j| < t$ is significantly larger than those awaited in a random distribution: it is an indication of synchrony within a time lag t between the two sets of events. Similarly, values of $L_{VE}(t)$ within the confidence envelope indicate independence, while values falling under the confidence envelope indicate asynchrony or repulsion. In the following, the synchronization of events is explored graphically by means of their smoothed time densities, while it is assessed formally examining the $L$-function. The analysis updates that performed in [12] for an older version of the earthquake catalog.

The eruptive history of Mt Vesuvius between the seventeenth century and the beginning of the twentieth century is illustrated in **Figure 2a**. After a long period of weak activity (6 eruptions since 1100, including a VEI 2 eruption on 1500 and a VEI 1 eruption on 1570), the volcano

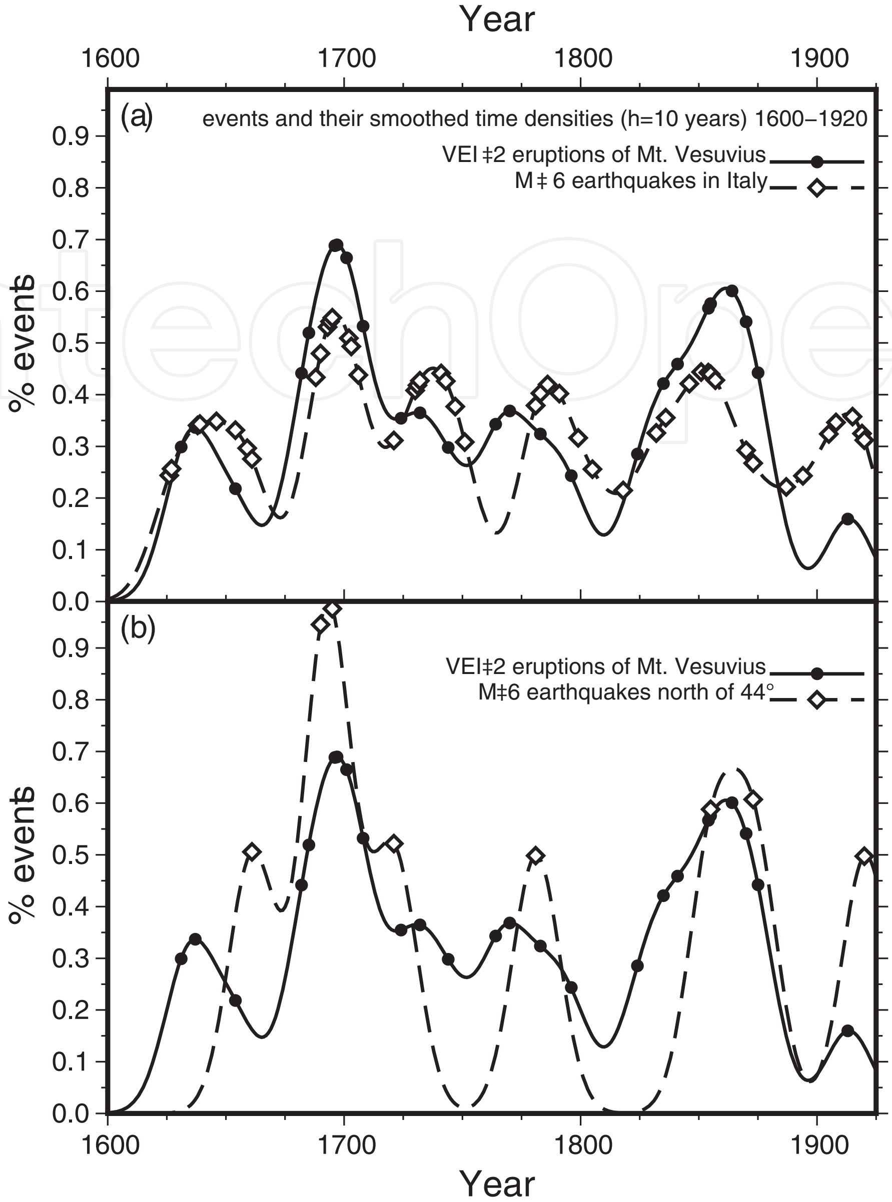


**Figure 2.** Time distribution of strong earthquakes in Italy compared to Vesuvius' eruptions in the time period 1600–1920: (a) seismicity of the entire territory; (b) earthquakes located north of 44° lat.

reactivated with the strong eruption of 1631 (VEI 5), followed by 24 eruptions (4 with VEI = 2, 19 with VEI = 3, and 1 with VEI = 4). Their smoothed time densities computed for h = 10 years (continuous line in **Figure 2a**) indicate two peaks around 1700 and 1850, as well as an overall oscillatory behavior with a time period of about 50 years. Such trend is very similar to that of the earthquakes (dashed line in **Figure 2a**). Eruptions and earthquakes appear almost synchronous on six regular oscillations. The characteristics of such oscillations were explored graphically in [6]. A more formal test based on Schuster spectrum analysis [26] has been adopted in [13] for the oscillations of seismicity. It demonstrates the statistical significance of the oscillations and refines the estimation of their time period to 46 years. Applied to the set of Vesuvius' eruptions the same test fails, indicating that the oscillations are too weak to gain a statistical significance. Nonetheless, the similarity between the two smoothed time densities is such to suggest a formal test for synchronization. The L-function and the corresponding 95% envelope computed for the two sets of events are traced in **Figure 3a**. The time correlation is significant for the time lags of 3 and 9 years, where the L-function exceed the 95% envelope. **Figures 2b** and **3b** show the same comparison performed for 9 earthquakes located above the 44th parallel north (evidenced with dashed line in **Figure 1**), at more than 400 km from the Vesuvius. Even in this case, the two time densities are similar, with a good correspondence on the two peaks near 1700 and 1850 and less precision on the other local maxima, especially before 1700. The L-function (**Figure 3b**) reflects such deteriorated time correlation: the 95% envelope (dashed line) is just touched for a time lag of 3 years, while there is a widespread time synchronization significant at the 90% confidence level (dotted line) for various time lags up to 25 years, the semi-period of oscillation. Such result indicates that there is some degree of overlapping among the positive part of the oscillations, near the local maxima.

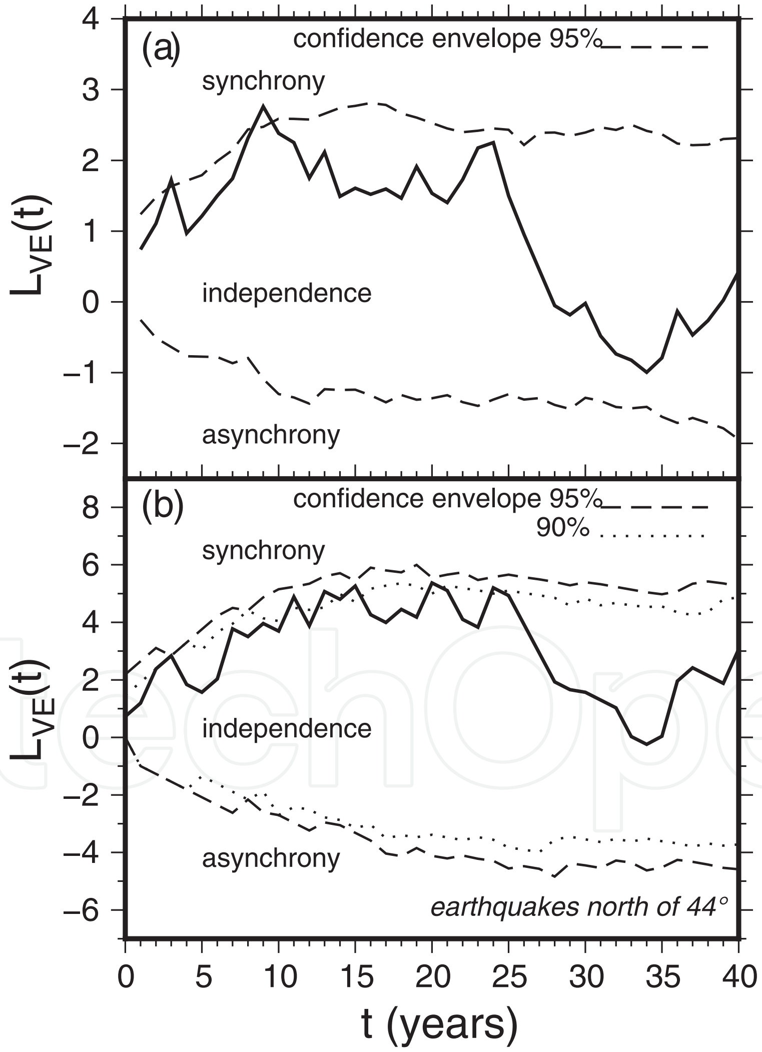


**Figure 3.** L-function in the modified Ripley's test for synchronization [23–25] applied to the series of strong earthquakes in Italy and Vesuvius' eruptions occurred in the time period 1600–1920: (a) seismicity of the entire territory; (b) earthquakes located north of 44° lat.

## 4. Further check on the possible volcanic triggering by earthquakes: the case of the Campi Flegrei caldera

After more than three centuries of quiescence, with almost continuous deflating, the Campi Flegrei caldera reactivated around 1950 and, since then, has been subjected to uplift steps of various amplitudes. The vertical movements are documented since 1905 by irregular geodetic levelings and indirect measurements [20], as well as, since 2000, by continuous GPS data [21]. Such a time series, its correlation with strong seismicity and the complementarity with the eruptions of Mt Vesuvius are shown in **Figure 4**. The last eruptive phase of Vesuvius (1913–1944) coincides with the largest seismic oscillation of the last century (peak around 1920), with the Campi Flegrei slowly deflating. Around 1950, the situation is inverted, with the Vesuvius at rest and the caldera that reactivated with two major episodes on 1970 and 1983 almost synchronous with the second (both in amplitude and chronologically) oscillation of seismicity. Around 2004, the caldera started a slower and more reduced uplift phase, currently still active, that coincides with the last, less energetic cycle of seismicity (three earthquakes: 2009, L’Aquila, Mw 6.3; 2012, Emilia, Mw 6.1; and 2016, Central Italy, Mw 6.2).

For the last century, the seismic catalog is complete at a much lower magnitude threshold (Mw 4.8 according to [19]) and the magnitude estimation itself is more reliable. This allows performing a direct comparison between the uplift and the energy radiated by the earthquakes, a quantity which is sampled at a larger number of points than in previous analysis

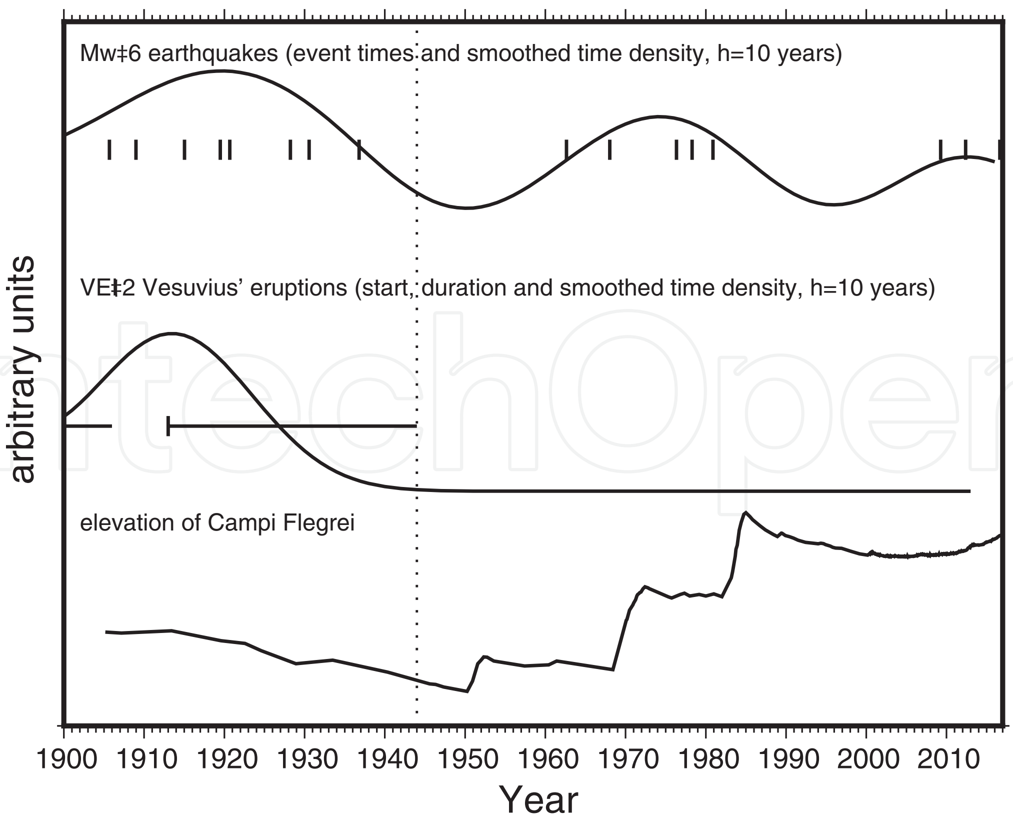


**Figure 4.** Smoothed time density of Mw ≥ 6.0 earthquakes in Italy since 1900 (top) compared to the smoothed time density of Vesuvius’ eruptions (middle) and the elevation of the Campi Flegrei caldera (bottom).

(127 mainshocks with Mw ≥ 4.8 since 1950 compared to 8 with Mw ≥ 6). The relationship is illustrated in **Figure 5** for the cumulative uplift (the deflating phases were removed) and the cumulative radiated energy $E_S$ expressed in erg computed from Mw according to the equation

$$\log_{10}(E_S) = 1.5\,M_W + 11.8 \tag{4}$$

drawn from [27]. Since 1950, the vertical movements and the cumulative earthquake energy chase each other, according to an irregular pattern (uplift steps either precede or follow periods of major energy release). Concerning the possible triggering of the uplift by earthquakes, just one step is clearly preceded by a strong earthquake located near the seismo/volcanic coupling zone (SVCZ in the following) delineated in [5]: step S3 in **Figure 5** (1983), preceded by the 1980 Irpinia earthquake (Mw 6.8, located about 95 km east of the caldera). Of the other steps, that of 1952 (S1 in **Figure 5**) has no significant seismicity preceding it; that of 1970 (S2) is preceded by the 1968 Belice earthquake (Mw 6.4), located in Sicily, at more than 300 km from the caldera, while the previous significant earthquake in the SVCZ occurred 8 years before the uplift (1962 Irpinia earthquake, Mw 6.2, located 80 km north-east of the caldera). The more gradual uplift that started on 2004 (S4, shown in detail in **Figure 6**) was preceded on 2002 by two moderate earthquakes, one (Mw 5.9) located externally to the SVCZ in the Tyrrhenian sea (270 km south-east of the caldera) and the other one, with Mw 5.7, located within the SVCZ, 120 km north-east of the caldera (2002 Molise earthquake). After 2004, the uplift goes strictly in parallel with the energy release, with the three strong earthquakes of 2009, 2012, and 2016 located externally to the SVCZ, in central and northern Italy (172, 509, and 221 km north-west of the caldera, respectively). As a consequence, if a triggering effect exists, it is rather fuzzy. In particular, it should involve earthquakes that are external to the SVCZ (e.g., those post-2004) with response times that are not proportional to the distance (e.g., the 1962 earthquake, the nearest to the caldera, which could have triggered an uplift with a delay of 8 years).

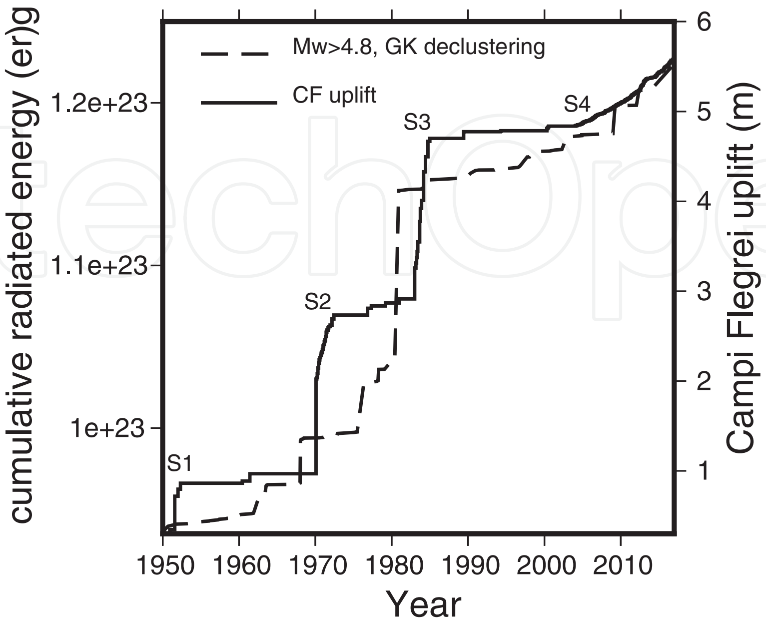


**Figure 5.** Comparison between the uplift time series of the Campi Flegrei caldera (deflating episodes removed) and the cumulative energy released by earthquakes with Mw ≥ 4.8 occurred in Italy in the time period 1950–2016.

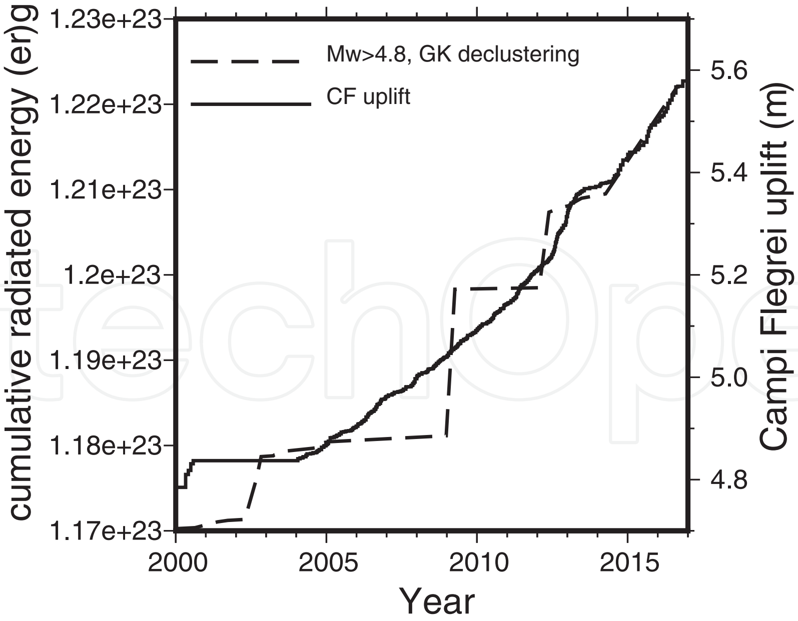


**Figure 6.** Comparison between the uplift time series of the Campi Flegrei caldera (deflating movements removed) and the cumulative energy radiated by earthquakes with Mw ≥ 4.8 occurred in Italy in the time period 2000–2016.

## 5. Eruptions, earthquakes, and the climate

The facts described so far suggest that point-to-point elastic stress transfer alone is not sufficient to explain the large-scale seismic/volcanic correlation involving the Neapolitan volcanic district. Perhaps, more general mechanisms should act. Previous works [6, 12, 13] noted the correspondence between the seismic transient that took place between 1600 and 1900 (three time the annual rate of destructive earthquakes in respect to the previous period) and the occurrence of the Little Ice Age (LIA). Furthermore, the current phase of global warming is synchronous with the gradual reduction of seismic activity through the last century (**Figure 4**). Previous works have suggested a possible role of the climate, which could affect both the seismicity and the volcanism through variations of the surface loads (sea level, ice at the poles and glaciers) and consequent changes of the stress field at depth. A similar mechanism is supported by a number of geophysical models and statistical studies available in the literature [28], although most of them (e.g., [29]) refer to the deglaciation and the sea level increase (about 120 m) that followed the last glacial maximum of 21,000 years ago.

What outlined is a promising field of investigation, although very problematic. Just to say, there are a number of climate indexes, most of which are not direct measures but reconstructions obtained by correlation with biological, chemical, and geophysical data. There is no consensus on the beginning of the LIA as well as on its spatial extension (global or restricted to a more limited area, for example, the Euro-Asiatic region) and its temporal evolution. All such complicates the assessment of the time correlation, which is just the first step of the task. The work [6] reports some graphical comparisons between Italian seismicity, the global sea level, and the global sea level rate, since 1700. More robust statistical methods are adopted in [12] to assess the degree of correlation between Italian seismicity of the last millennium and a reconstruction

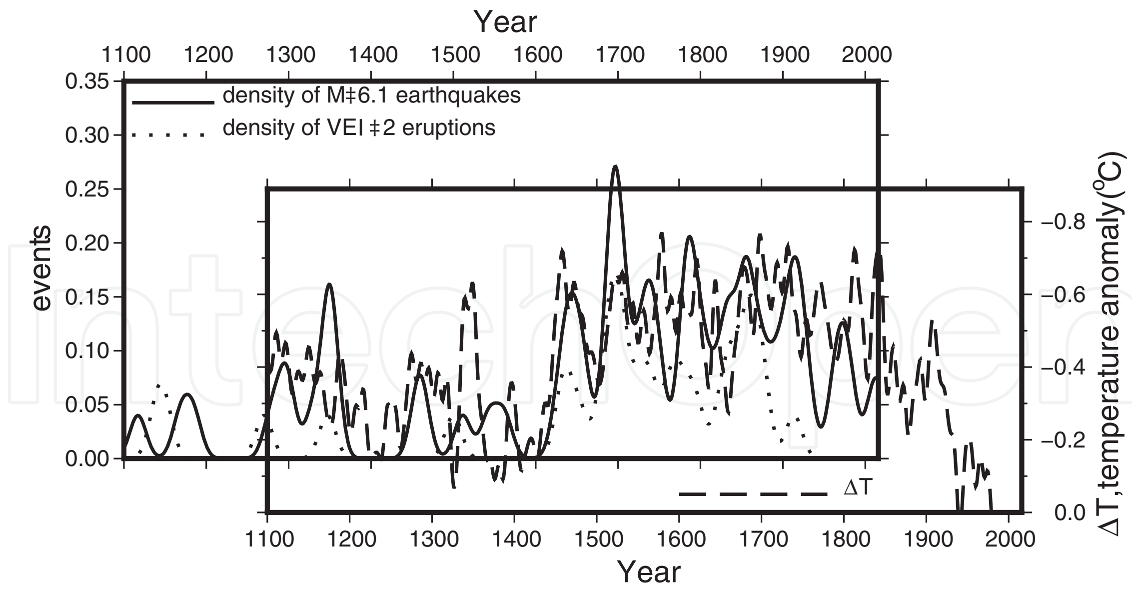


**Figure 7.** Comparison among the smoothed time density of Mw ≥ 6.1 earthquakes occurred in Italy since 1100, the smoothed time density of VEI ≥ 2 eruptions of Mt Vesuvius, and a reconstruction of the global surface temperature anomaly ΔT [30]. The plot of temperature is reversed (increasing values downward) and shifted by 174 years to evidence the estimated anticorrelation with the earthquakes.

of the global surface temperature [30]. In that case, a point process (the sequence of Mw ≥ 6.1 earthquakes in Italy occurred since 1100) was compared with a continuous time function (the time series of temperature) using binomial logistic regression [31]. The analysis found a significant negative correlation for a time lag of 174 years: the probability to have an earthquake during the year $y$ has a negative dependence on the temperature recorded 174 years before (the higher the temperature, the lower the probability of an earthquake). The relationship is illustrated in **Figure 7** (modified from [12]), where the smoothed time density of earthquakes (continuous line) is plotted together to the time series of the global surface temperature anomaly ΔT (difference with the mean temperature in the reference period 1961–1990, dashed line), with the y-axis reversed (increasing values downward) and the x-axis translated by 174 years. In addition (in respect to the original figure), **Figure 7** reports the smoothed time density of the Vesuvius' eruptions (dotted line): even such curve matches the negative temperature anomaly, although the eruptive activity stops in the first half of the twentieth century.

The transformation from global surface temperature to water/ice surface load is not so immediate. Also, the physical justification of a delay of 174 years could be problematic. It is possible that other, even more local climate indexes are more appropriate. The paper [32] describes the common behavior of glaciers and lakes in west-central Europe over the last 3500 years. Representative of this, the authors report the advance/retreat time history of the Great Aletsch glacier (Alps of Valais, Switzerland), the largest glacier in the European Alps. In **Figure 8**, such data are compared with the time densities of Mw ≥ 6 earthquakes in Italy and VEI ≥ 2 Vesuvius' eruptions since the year 1100 (as the glacier data are given with low detail, the densities are smoothed for a large smoothing parameter, h = 40 years). The resemblance among the three curves is remarkable. In the post-1600 period, they share the bimodality with time lags extremely reduced in respect to the comparison with the temperature (about 50 years for the peaks near 1700). In the pre-1600 period, they have three common oscillations, although with

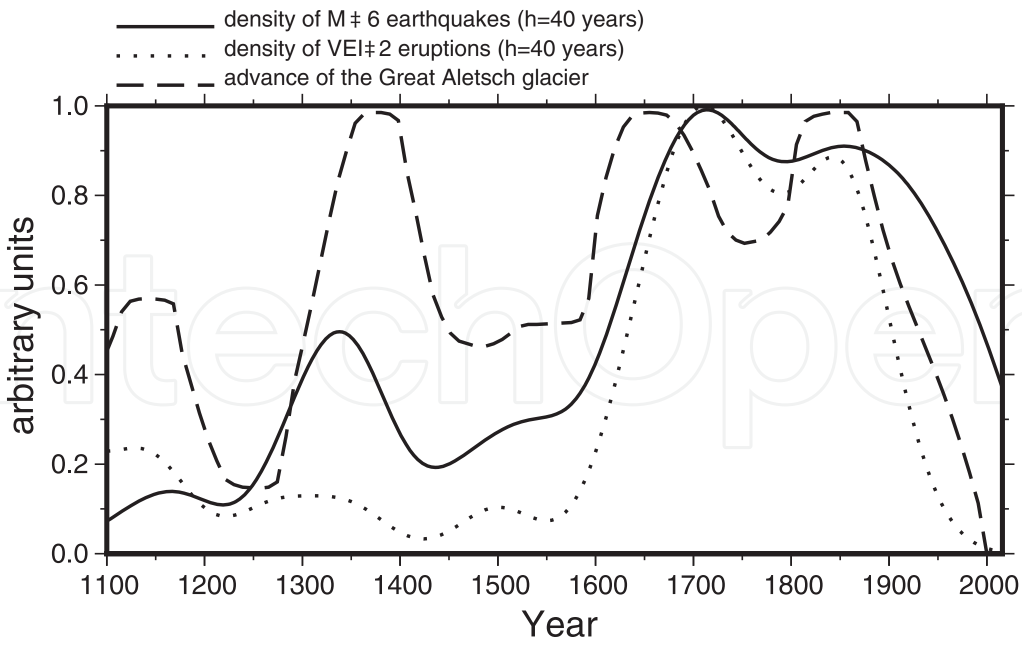


**Figure 8.** Comparison among the smoothed time density of Mw ≥ 6.0 earthquakes occurred in Italy since 1100, the smoothed time density of VEI ≥ 2 eruptions of Mt Vesuvius, and the fluctuation (increasing values indicate advance) of the Great Aletsch glacier according to [32].

different amplitude. The figure offers also an example of the lack of direct correspondence between temperature and ice extension. In fact, the Great Aletsch glacier was at a local minimum around 1450, a period characterized by low global temperature (**Figure 7**). Such finding indicates that other factors must be taken into consideration (e.g., the precipitation regime).

## 6. Conclusions

The analysis of updated and new data confirms the existence of a close relationship between the Italian seismicity and the volcanic activity in the Neapolitan area. Such a correlation involves not only the Mt Vesuvius but also the Campi Flegrei caldera, which was reactivated with a significant rate of uplift during the last 70 years. This type of seismic/volcanic correlation was previously explained as the effect of the elastic stress transfer from earthquakes sharing the same tectonic environment of the volcano (southern Apennines). This view implies a rather specific, event-to-event correspondence between earthquakes and eruptions. The evidences furnished in the present chapter indicate a looser, less specific correspondence, where the volcanic activity reflects the time density of a population of earthquakes, including also events located in northern Italy, an area dominated by a rather different stress regime (compressive instead of distensive). Continuous data from the geodetic monitoring of the Campi Flegrei also suggest that the time correlation is less episodic (i.e., related to events) and involves also a smooth evolution (e.g., the rather regular expansion of the caldera since 2004 illustrated in **Figure 6**). The picture here outlined suggests an alternative, common mechanism at the basis of both types of activity. The load/unload of the earth surface by climate processes is a possible candidate. The graphical comparison of **Figure 8** suggests that regional (e.g., European) instead of global effects should be considered. The last point of interest emerging from the seismic/volcanic comparative analysis is the observed complementary behavior between the Vesuvius and the Campi Flegrei caldera. Although it could be a purely accidental effect, it encourages a holistic approach that looks at the Neapolitan volcanic district as a single integrated system rather than a set of distinct volcanoes.

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