frontiers in Earth Science

BRIEF RESEARCH REPORT
published: 02 November 2021
doi: 10.3389/feart.2021.758602

Modulation of Ground Deformation and Earthquakes by Rainfall at Vesuvius and Campi Flegrei (Italy)

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Volcanoes are complex systems whose dynamics is the result of the interplay between endogenous and exogenous processes. External forcing on volcanic activity by seasonal hydrological variations can influence the evolution of a volcanic system; yet the underlying mechanisms remain poorly understood. In the present study, we analyse ground tilt, seismicity rates and rainfall amount recorded over 6 years (2015–2021) at Vesuvius and Campi Flegrei, two volcanic areas located in the south of Italy. The results indicate that at both volcanoes the ground deformation reflects the seasonality of the hydrological cycles, whereas seismicity shows a seasonal pattern only at Campi Flegrei. A correlation analysis on shorter time scales (days) indicates that at Vesuvius rain and ground tilt are poorly correlated, whereas rain and earthquakes are almost uncorrelated. Instead, at Campi Flegrei precipitations can affect not only ground deformation but also earthquake rate, through the combined action of water loading and diffusion processes in a fractured medium, likely fostered by the interaction with the shallow hydrothermal fluids. Our observations indicate a different behavior between the two volcanic systems: at Vesuvius, rain-induced hydrological variations poorly affect the normal background activity. On the contrary, such variations play a role in modulating the dynamics of those metastable volcanoes with significant hydrothermal system experiencing unrest, like Campi Flegrei.

Keywords: Vesuvius, Campi Flegrei, ground tilt, earthquakes, rainfall

OPEN ACCESS

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Specialty section:
This article was submitted to Volcanology, a section of the journal Frontiers in Earth Science

Received: *14 August 2021*
Accepted: *11 October 2021*
Published: *02 November 2021*

Citation:
Petrosino S, Ricco C and Aquino I (2021) Modulation of Ground Deformation and Earthquakes by Rainfall at Vesuvius and Campi Flegrei (Italy). Front. Earth Sci. 9:758602. doi: 10.3389/feart.2021.758602

INTRODUCTION

In the recent years an increasing number of observations has been showing how rainfall-induced stress variations play a role in modulating ground deformation and seismic activity. Meteoric water storage and load can produce surface deformation, inducing crustal stresses and modulating seismicity (Craig et al., 2017). In addition, variations of the pore-fluid pressures induced by rainfall can promote both ground deformation (Kümpel et al., 2001; Dal Moro and Zadro, 1998; Westerhaus and Welle, 2002; Lesparre et al., 2017) and earthquake nucleation, often with seasonal patterns well correlated with precipitations (Muço, 1999; Heinzl et al., 2006).

The modulation of ground deformation and seismicity by rainfall assumes a critical role in volcanic environments because it superimposes on the endogenous processes and may influence the volcano dynamics. In particular, for those volcanoes in magmatic/hydrothermal unrest or prone to eruption, meteoric input can act as a trigger for volcanic activity. This interaction occurs on typical time scales going from hours, to days and months. As an example, the effect of meteoric water load and the subsequent interaction with groundwater at Nevado del Ruiz (Colombia) possibly caused deformation events and triggered phreatic explosions and seismicity occurred through 1985–1988 (Banks et al., 1990). The study of the seasonal pattern of eruptions over more than 150 years of available records at Piton de la Fournaise (La Réunion) suggested to explore the possible link with rainfall, by modelling the volumetric ground deformation in response to a water loading/unloading mechanism (Violette et al., 2001). At Soufrière Hills volcano (Montserrat, Lesser Antilles), the response of seismic activity to intense precipitations observed over 3 years (2001–2003) of monitoring has been attributed to both shallow and deeper fluid/solid interactions occurring at different time scales (from hours to days) and related to the percolation of water into cracks (Matthews et al., 2002, 2009). The authors conclude that the rainfall modulates existing, internal processes, rather than generating new events itself. Extreme rainfall is supposed to have triggered the 2018 rift eruption at Kīlauea volcano (Hawaii), by increasing the pore pressure at depths of 1–3 km and promoting the mechanical failure of the volcanic edifice (Farquharson and Amelung, 2020). It is noteworthy that the eruption was not caused by the forceful intrusion of new magma into the rift zone, but by a dyke propagation prompted by meteoric water infiltration. Also the statistical analysis of the occurrence of historical eruptions at Kīlauea strongly suggests a correlation between rainfall and volcanic activity (Farquharson and Amelung, 2020).

In the present paper we investigate and compare the possible links among rainfall, ground deformation and seismicity at two of volcanoes currently characterized by different activity: Vesuvius, which is in a quiescent state, and Campi Flegrei, a caldera experiencing unrest.

Vesuvius and Campi Flegrei are potentially dangerous volcanoes located in the area of Naples (Southern Italy). Vesuvius is a stratovolcano which experienced its last eruption in 1944 (Sbrana et al., 2020). It is characterized by a great variability in eruptive style: highly explosive, sub-Plinian and Plinian eruptions alternating with periods of Strombolian and effusive open-conduit activity, that typically followed long periods of quiescence (Cioni et al., 2008 and references therein). After the last subplinian eruption, in 1631, Vesuvius was marked by open-conduit activity, which ended with the eruption of 1944. The alternating activity of Vesuvius resulted in different deposits including lavas and pyroclastic products. The ground deformation inferred from more than 20 years of tiltmeter signals shows a common subsidence pattern of the southern part of the volcanic edifice, related to joint effects of gravitational sliding and extensional tectonic stress (Ricco et al., 2013, 2021). This background tilt showed gradual or abrupt interruptions in both trend and amplitude during phases of high seismic activity (Ricco et al., 2021), resulting in more complex deformation patterns and indicating a close link between ground tilt and seismicity. The most significant episodes related to variations of internal dynamics occurred in 2017–2019 (Ricco et al., 2021). Vesuvius seismicity consists mainly of volcano-tectonic (VT) earthquakes of low-to-moderate magnitudes (up to 3.6) and mainly located along the crater axis, up to a depth of 6 km below sea level (bsl) (Madonia et al., 2008). The source mechanisms are related to the interaction of the regional and local stress fields, as well as to fluid-driven rock fracturing triggered by pressure variations in the shallow hydrothermal system. Since 2003, low-frequency (LF) and long-period (LP) earthquakes have been observed and associated with mechanisms of brittle slow failure of dry rocks, and resonance of pre-existing fluid-filled cracks, respectively (Bianco et al., 2005; Petrosino et al., 2020a). At Vesuvius a correlation between rainfall and seismicity has not yet been observed; modulation of seismic activity on short (daily) time scales has been interpreted to be linked to a number of possible mechanisms related with the cooling/warming diurnal cycle of the volcanic edifice and/or with the daily oscillation of the geomagnetic field (Mazzarella and Scafetta, 2016). On long time scales (decades) it has been hypothesized that sea level changes could modulate the eruptive cycles (Bragato, 2015).

Campi Flegrei is a caldera generated by at least two major collapses, related to the Campanian Ignimbrite (~39 ka), and the Neapolitan Yellow Tuff eruptions (~15 ka). The caldera experiences slow subsidence alternating with fast ground uplift accompanied by seismicity. After the last eruption of Monte Nuovo in 1538, Campi Flegrei experienced a phase of subsidence, followed by episodes of uplift between 1950–1952 (about 0.75 m), 1969–1972 (1.77 m), and 1982–1984 (1.79 m). Since 1985, the area has undergone a further phase of subsidence, with only brief uplift events recorded in 1989, 1994, and 2000. A new episode of ground uplift started in 2005 and it is still ongoing with accelerated rate during 2011–2013 and subsequently since September 2020; to date the overall vertical deformation is about 0.8 m. Uplift episodes are likely related to the pressurization of hot fluids (CO_2 and H_2O) exsolving from a deep magmatic body towards a shallow hydrothermal system where they mix with meteoric components (Gresse et al., 2017). Hydrothermal fluids and gases are released at the surface of Solfatara crater and Pisciarelli fumarolic field, the most thermally active sites of the caldera (Caputo et al., 2020; Cusano et al., 2021). Uplifts are accompanied by seismicity consisting of both sequences of VT earthquakes and LP events. The most remarkable LP swarm occurred in October 2006 (Saccorotti et al., 2007; Falanga and Petrosino, 2012; De Lauro et al., 2012) and it was located at depths of about 500 m bsl beneath the Solfatara crater. The LP generation mechanism is related to the acoustic resonance of a crack filled by a water-gas mixture of hydrothermal origin (Cusano et al., 2008). The VT activity is characterized by the alternation of swarms lasting a few hours, and phases of low seismicity rate (Petrosino et al., 2018; Bellucci Sessa et al., 2021). Since 2018 the activity is increasing and the most relevant earthquakes (Md 3.1 and 3.3) occurred on December 6th, 2019 and April 26th, 2020. The earthquakes are mainly located beneath the Solfatara-Pozzuoli area, at depths up to 4 km bsl, with the highest concentration between 1–2 km bsl (Bellucci Sessa et al., 2021). The source mechanism is a brittle shear failure induced by the pressurization of the hydrothermal system and the consequent fluid flow towards the surface (Saccorotti et al., 2007). As shown in recent works, there is evidence that the volcanic system responds the to the rainfall both in term of ground deformation and seismic activity. In particular, diffusive processes into the highly fractured rocks,

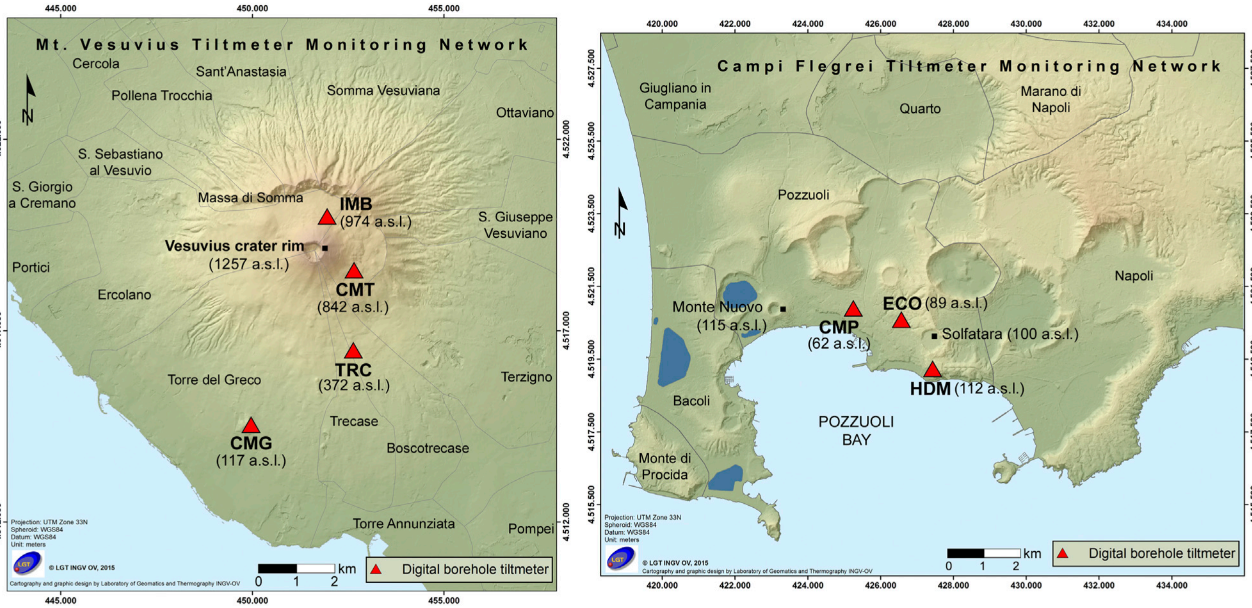

FIGURE 1 | Map of Vesuvius **(A)** and Campi Flegrei **(B)** with the location of the borehole tiltmeters. The base maps were created by the INGV-OV Laboratory of Geomatics and Thermography, © LGT INGV OV, 2015.

pore pressure and permeability variations have been advocated to explain the correlation between rain and ground tilt (Ricco et al., 2019; Petrosino et al., 2020b), as well as rain and seismicity (Petrosino et al., 2018, Scafetta and Mazzarella 2021).

In continuity with the previous studies, in the present work we perform a statistical correlation analysis of the time series of ground tilt, seismicity rates and rainfall amount recorded over 6 years (2015–2021). The results indicate that, although at both Vesuvius and Campi Flegrei ground deformation is sensitive to the input of meteoric water, the two volcanic systems respond in a different way to rain-induced hydrological variations. In particular, at a stressed caldera like Campi Flegrei the rainfall can modulate not only ground deformation on different time scales but also earthquake rate. These observations suggest that the Campi Flegrei dynamics is the result of a complex interplay between endogenous and exogenous processes.

DATA AND METHODS

The borehole tiltmeter network at Vesuvius is currently composed of four instruments (TRC, IMB, CMG and CMT) which started to operate contemporaneously since September 2016 (**Figure 1**). At Campi Flegrei the network consists of three borehole tiltmeters (CMP, ECO and HDM) working since 2015 (**Figure 1**). Both networks are managed by Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli–Osservatorio Vesuviano (INGV-OV). The tiltmeter stations consist of digital sensors model “Lily Self-Leveling Borehole Tiltmeter” equipped with a self-leveling bubble electrolyte with a dynamic range of ±330 μradians and a resolution less than 5 nradians. The tiltmeter package includes a magnetic compass and a temperature sensor. Ground tilt variations are measured along two orthogonal directions NS and EW; they are recorded with a sampling rate of 1 sample per minute. The depths of the bore hole installations range from 20 to 28 m (Ricco et al., 2018).

We used tiltmeter data from October 1st 2016 to March 31st 2021 for Vesuvius, and from April 1st 2015 to March 31st 2021 for Campi Flegrei. The number of VT earthquakes for the same time intervals was obtained by the INGV-OV seismic catalogue, available at the url (https://www.ov.ingv.it/index.php/cataloghi-sismici-vulcani-napoletani?category[0]=73&category_children=1&own=0, last access 2021/04/30). Rainfall amount data sampled at 1 day for Pozzuoli and Torre del Greco towns were downloaded by the historical archive of the website https://www.3bmeteo.com/meteo/ora/storico (last access 2021/04/30).

Borehole tilt signals contain several components: trend (which is often related to the dynamics of the area and consists of net movement), seasonal and tidal deformation, and a residual which is related to isolated events (such as earthquakes), rainfall-induced deformation and short period (less than a few days) fluctuations (Kümpel et al., 2001; Garcia et al., 2010; De Lauro et al., 2018). The typical representation of tilt data (cumulative deformation over a certain time interval; **Supplementary Figure S1**) highlights the long period trend, minimizing short period noise which is often considered as a disturbance to discard. An equivalent way to represent data is by differencing the time series (Chatfield, 2013): in this case data will reveal short term variations, with the trend being removed. Thus, considering the time derivative of the tiltmeter signals is a useful approach to compare the ground deformation with rainfall amount (Breitenberger, 1999; Dal Moro and Zadro, 1998).

For our analyses, we used the differenced ground tilt and calculated the root mean square (RMS) according to:

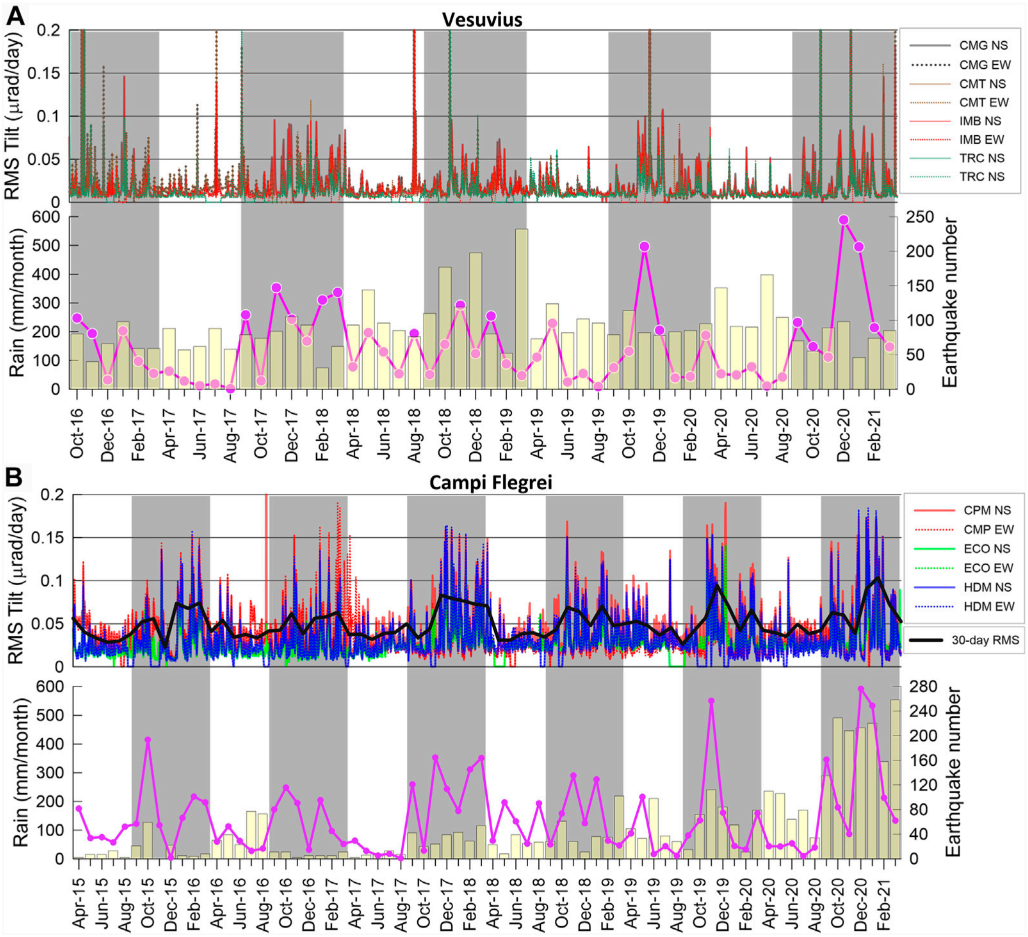

FIGURE 2 | Daily RMS tilt and monthly distribution of rainfall **(purple line)** and earthquakes **(yellow bars)** at Vesuvius **(A)** and Campi Flegrei **(B)**. The light-grey boxes in the background mark the wet season of the hydrological year. For Campi Flegrei, the RMS tilt calculated over a 30-day time window and averaged over the components of all instruments is also shown **(black line)**.

$$x_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

where x represents the time series and N is the number of samples in the selected time window. After having tried several durations between 1 and 30 days, we chose a 1-day time interval, long enough to stabilize fast ground tilt fluctuations/oscillations, nevertheless still suitable to show evidence of ground deformation at short time scales. This is a good compromise between too much detail and a too generalized overview. Thus, the obtained RMS represents an estimate of the daily average ground tilt.

We estimated the cross-correlation among RMS tilt, rainfall amount and earthquake number in order to obtain an indication of the similarity of the time series as a function of the time lag (Chatfield, 2013). The normalized cross-correlation function is defined as:

$$C_{xy}(k) = \frac{1}{N\sqrt{C_{xx}(0)}\sqrt{C_{yy}(0)}} \sum_{i=1}^{N-k} (x_i - \mu_x)(y_{i+k} - \mu_y)$$

where N is the number of samples, (μ_x, μ_y) and ($\sqrt{C_{xx}(0)}$, $\sqrt{C_{yy}(0)}$) denote the mean and the zero lag autocorrelation of the time series, and $k < N$ are positive integer values. The maxima (or minima if the signals are negatively correlated) of the cross-correlation function correspond to the points in time where the signals are best aligned. It is important to remark that correlation tests a relationship between two variables, but it does not imply causation.

RESULTS

A generalized overview of the temporal pattern of ground deformation, earthquakes and rainfall throughout the entire time interval of analysis is shown in **Figure 2**, in which we compare the daily RMS of both the components of the ground tilt, and the monthly distributions of VTs and rainfall amount. A simple visual inspection shows the seasonality of the RMS tilt at both Vesuvius and Campi Flegrei areas, reflecting the pattern of

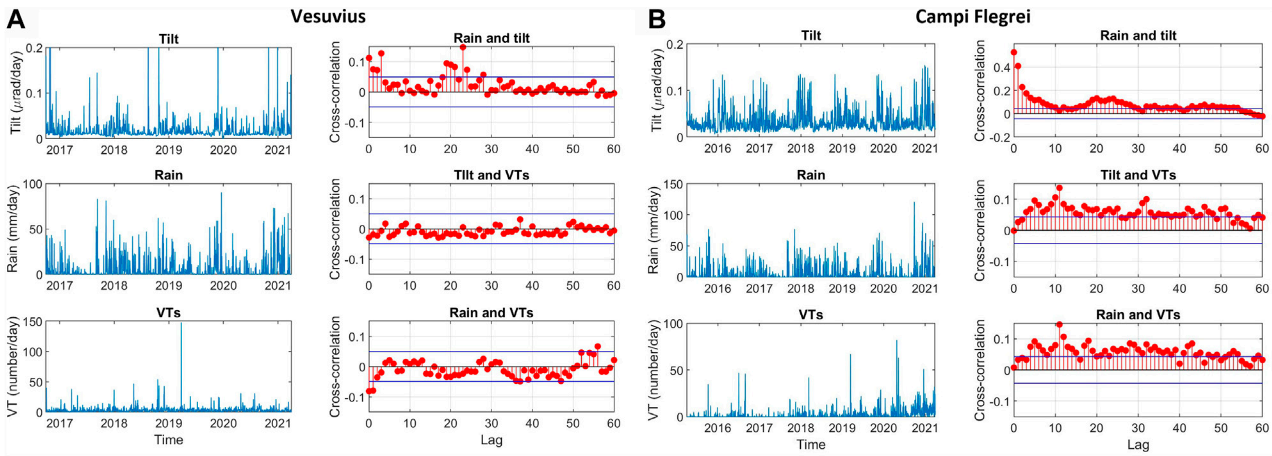

FIGURE 3 | (A) On the left, daily values of RMS tilt, rainfall and earthquake number for Vesuvius. On the right, cross-correlation functions among the three time series (lag = 1 corresponds to 1 day). The blue horizontal lines mark the confidence limits (95%), above which the correlation between the time-series is considered significant. **(B)** On the left, daily values of RMS tilt, rainfall and earthquake number for Campi Flegrei. On the right, cross-correlation functions among the three time series.

the hydrological year (Petrosino et al., 2018). The comparison among the time series indicates a possible correlation among the three physical observables (especially between tilt and rainfall), which appear more evident at Campi Flegrei. The patterns of the RMS tilt (nearly overlapped in **Figure 2**) are almost independent of the site, as confirmed by the estimates of the cross-correlation matrix among the different tilt components and sensors (**Supplementary Figure S2**). Such analysis provides correlation coefficients greater than 0.75 for the tiltmeters installed at both areas (except for TRC site, which has a slight lower value), suggesting a common origin of the observed daily average tilt.

A further observation regards the RMS values of the tilt at Campi Flegrei which are higher than those recorded at Vesuvius: with the exception of few peaks, RMS is far below <0.05 μrad/day in the dry season and <0.1 μrad/day at Vesuvius, while at Campi Flegrei these thresholds are often exceeded. This behavior suggests that the daily induced ground response to rainfall is more prominent at Campi Flegrei.

The cross-correlation analysis of the daily sampled time series provides further insights. In order to have a mean spatial estimate of the cross-correlation functions, at Campi Flegrei we averaged the RMS of the tilt over all the components and instruments. At Vesuvius we excluded the time series recorded at TRC site from the average estimate, considering its lower correlation with the signals acquired at the other three instruments. Moreover, at Campi Flegrei we extracted from the seismic catalogue only earthquakes with inter-event times less than 1 day because it has been inferred that this clustered seismicity (often grouped in intense seismic swarms) is closely related with exogenous processes, while the background seismicity (inter-event times >1 day) accounts for endogenous dynamics (Petrosino et al., 2018).

The results are shown in **Figure 3**. In general, at Vesuvius the correlations among the time series are low ($C(k) < 0.2$). Maxima values of correlation between tilt and rain occur at lags [0–4] and [19–24]. Tilt and VTs as well as rain and VTs are almost uncorrelated at least at the daily time scale (**Figure 3A**). A similar analysis performed only on the ground tilt recorded at TRC site confirms the low degree of correlation among tilt, rain and VTs (**Supplementary Figure S3**).

The cross-correlation among rainfall, ground tilt and earthquakes at Campi Flegrei shows a different pattern. From **Figure 3B**, the maximum value (0.53) of cross-correlation between RMS tilt and the rainfall daily time series is at zero lag (within the 1-day uncertainty which corresponds to the sampling rate of the available rainfall data) suggesting a nearly instantaneous response of the ground deformation to meteoric input. Then, the cross-correlation function smoothly decreases during the first 10 days, indicating a persistent relationship between the two observables. Moreover, although seismicity and tilt, as well as seismicity and rainfall, appear poorly correlated, the corresponding cross-correlation functions have both a maximum value (above the 95% significance level) at a time lag of 11 days.

In order to take into account the eventual delay related to meteoric water diffusion into the ground, at Campi Flegrei data were further analysed by considering the RMS tilt, rainfall amount and VT number calculated over a time window of 30 days. Then we estimated the cross-correlation coefficients from the linear regression between rain and tilt as well as rain and earthquakes (**Figure 4A**). We observed an increase in both the cross-correlation values (0.77 rain and tilt, 0.36 rain and VTs) on 30 days, compared with the daily values. The obtained regression relationship between tilt and rain is:

$$y = 0.026 + 0.000086x$$

The equation provides an intercept value (0.026 μrad) which is consistent with the 30-day RMS tilt observed during dry seasons (black line in **Figure 2B**). In addition, referring to the time interval of 30 days, the regression law predicts an increase of 0.01 μrad/mm of the ground tilt for each increase of 120 mm of rain (which is the median values of the 6-year distribution of the

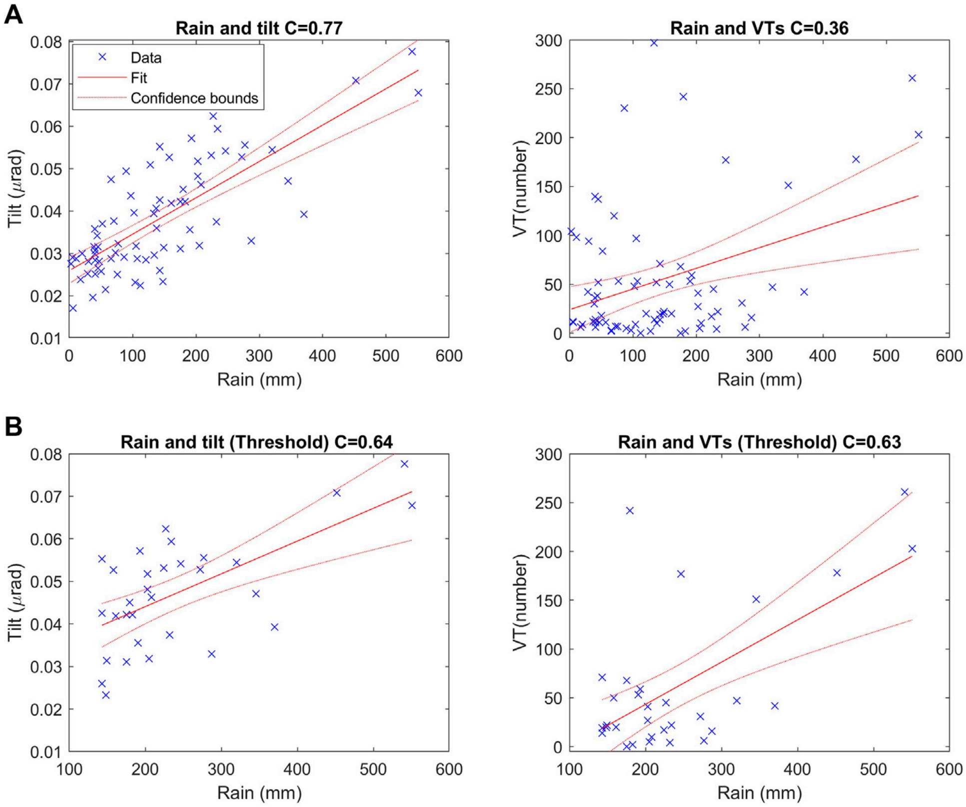

FIGURE 4 | Results of the regression analysis at Campi Flegrei. **(A)** On the left, linear regression between rainfall amount and RMS tilt. On the right, linear regression between rainfall amount and VT number. The red dotted lines mark the 95% confidence interval. All the variables have been estimated over a 30-day moving window. **(B)** On the left, linear regression between rainfall amount and RMS tilt, considering only rainfall values exceeding the 60th percentile of the 6-years distribution. On the right, linear regression between rainfall amount and VT number using the same rain threshold. The red dotted lines mark the 95% confidence interval. All the variables have been estimated over 30-day moving windows.

30-day precipitation amounts; **Supplementary Figure S4**). Such an increase is about two orders of magnitude lower that the monthly variations of the tilt rates related to the volcanic uplift (**Supplementary Figure S1**; https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/bollett-mensili-cf).

We also investigated the possibility of a threshold effect related to heavy and/or long-lasting precipitations. Because the average rainfall amount lies between the 45th and 55th percentiles of the total distribution (Knapp et al., 2015), we extracted only those RMS tilt and earthquake data corresponding to rainfall exceeding the 60th percentile (143 mm in 30 days) of the distribution calculated over 6 years (**Supplementary Figure S4**). In this case, the regression of the 30-day-average data provides correlation coefficients of 0.64 and 0.63 for rain and tilt and rain and VTs, respectively (**Figure 4B**). While the rain and VT cross-correlation increases considering the rainfall threshold, the rain and tilt cross-correlation is slightly higher when no threshold is applied. It is likely that the threshold introduction acts as a cut off for the nearly-instantaneous induced deformation effect and accounts mainly for the contribution related to a diffusive process.

DISCUSSION

Rainfall-induced ground deformations have been observed in many areas, especially for very shallow borehole instrument installations (Goulty, N. R., et al., 1979; Sakata and Sato, 1986; Roeloffs et al., 1989; Westerhaus and Welle, 2002; Kümpel et al., 2001; Lesparre et al., 2017). In our study cases, we notice a different behavior of the two volcanic areas of Vesuvius and Campi Flegrei. At Vesuvius a relationship between rainfall and ground deformation appears on seasonal time scale, as the RMS tilt shows amplitude variations which reflect the pattern of wet and dry seasons of the hydrological year (**Figure 2A**). On the daily time scale, the correlation between rainfall and ground tilt seems low. Moreover, no correlation with earthquakes is further observed at any of the investigated time scales.

At Campi Flegrei both the seasonal patterns of ground tilt (**Figure 2B**) and earthquake rates (**Figure 2B** and **Supplementary Figure S5**) have a striking similarity with the hydrological cycles, as the RMS tilt and VT number are systematically higher during the wet season. Here the seasonal tilt variations are more pronounced compared with those of Vesuvius. In addition, an evident correlation among rainfall, ground tilt and earthquakes also arises on the time scale of days. In particular, seismicity correlates with both rainfall and tilt (**Figure 3B**), with a delayed response which is focused at best when considering cumulative 30-days values and precipitation threshold (**Figure 4**). This suggests that a complex interplay among the three observables exists and that rainfall could have an impact on the dynamics of the system, as already pointed out in recent papers (Petrosino et al., 2018; Ricco et al., 2019; Petrosino et al., 2020b).

Several mechanisms have been proposed to take into account the possible hydromechanical coupling between rain and ground deformation observed in both tectonic and volcanic environments: among them, the most relevant are: 1) water loading essentially due to the ground compression by the added water mass, and 2) infiltration and diffusion processes which are able to modify the pore pressure of the medium (Kümpel et al., 2001; Westerhaus and Welle, 2002; Lesparre et al., 2017). The theory of poroelasticity (Wang, 2017; Wang and Kumpel, 2003) is able to explain the physical process at the origin of ground deformation related to water infiltration. According to this model, the tilt amplitude is proportional to the pore pressure gradient and depends on the rock poroelastic parameters. In the framework of the poroelasticity theory, variations of the pore-fluid pressure also play an important role in the generation of earthquakes, especially in hydrothermal/volcanic environments (Madonia et al., 2008; Savage et al., 2015; Ricco et al., 2021). Triggering of fluid-induced seismicity can be activated by diffusive processes related to pore pressure and permeability changes in porous and/or fractured saturated rocks (Shapiro et al., 2003; Andajani et al., 2020).

At Campi Flegrei such a mechanism has been invoked to explain the rainfall triggering of VT earthquakes (Scafetta and Mazzarella, 2021). The authors suggest that rainfall water percolates into the highly fractured and water-saturated rocks, mixing with deeper hot hydrothermal fluids, thus inducing pressure and permeability changes. By using a time-delayed rain function to model the diffusion process inside the soil, a delay of some days to 1–2 weeks is estimated so that water percolation affects seismicity in the depth range of 0–2.5 km. In addition, statistical results indicate that time-delayed models, compared to rapid seismic response to water infiltration, provide the highest correlations between the rainfall and seismic events at Campi Flegrei and thus represent the most probable scenario (Scafetta and Mazzarella, 2021).

From our analyses of geophysical time series recorded at Campi Flegrei, both a nearly prompt response to rainfall and a delayed one arise. As inferred in past studies the effect of the rain on ground tilt can be both immediate and delayed (Wyatt and Berger, 1980; Westernhaus and Welle, 2002; Garcia et al., 2010; Lesparre et al., 2017). Recently, Meurers et al. (2021) show that water accumulation on the terrain surface causes short-term (a few hours) tilt and gravity changes, while long-term (>a few days/ weeks) variations occur frequently after long-lasting and/or heavy rain. On the other hand, seismic activity often appears as a lagged feedback to precipitations (Muço, 1999; Heinzl et al., 2006; Craig et al., 2017; Scafetta and Mazzarella, 2021). Therefore, on the basis of the existing mechanisms of hydrological response, we hypothesize a combined action of water loading (which is almost instantaneous) mainly effective on the ground deformation, and a diffusion process (on the time scale of 10–30 days), which also affect (besides the tilt) the seismicity. Indeed, the delay of 11 days of earthquake occurrence with respect to rain and ground deformation could likely be related to the time of the percolation of the shallow meteoric fluid in the fracture system of the medium. This is supported by the increase of the cross-correlation values cumulated on 30 days. We also have to consider an additional possible effect of the ground deformation which under the water loading and diffusive process generates itself elastic stress on the rocks, in turn favoring the occurrence of VTs.

Interestingly, the introduction of a threshold for the precipitation amount further increases the correlation between rain and VT number, suggesting that below a certain rainfall rate the diffusion process is only weakly effective in triggering earthquakes. This is consistent with the results of Scafetta and Mazzarella (2021) who found that seismic swarms are more likely to occur during wet days rather than in dry ones (see also **Supplementary Figure S5**). On the other hand, the correlation between rain and tilt slightly decreases when considering a minimum value for the precipitation amount, likely because the threshold could act as a cut off for the nearly instantaneous water loading effect of light rain on the ground deformation.

The results of the present paper provide the ground for systematical investigation of the link among tilt, seismicity and rain, identifying the RMS of instantaneous tilt on short/medium time scale (days, weeks) as a suitable observable which can better highlight (at least at the first-order) ground response to rainfall. Moreover, we have shown how the RMS pattern can enhance the seasonal behavior of the ground tilt time series; therefore it can be used as a quick indicator of seasonality in ground deformation data.

Interesting inferences can be obtained by cross-correlating the rainfall, RMS tilt and earthquake rates. Despite the assumption of a simple linear model to describe the ground response to rain (Garcia et al., 2010), we were able to highlight basic differences between Vesuvius and Campi Flegrei. The clearer response observed at Campi Flegrei, compared to Vesuvius, could be likely related to differences in the fracture density of the medium as well as in rock porosity and permeability (Zollo et al., 2006; Andajani et al., 2020; Ricco et al., 2021). Moreover, at Campi Flegrei the presence of a shallower aquifer, water saturated rocks and geothermal fluids (Gresse et al., 2017) can amplify the rain-induced ground response (Kümpel et al., 2001). The temperatures associated with the hydrothermal system (de Lorenzo et al., 2001; Zollo et al., 2006) and the presence of pressurized gases discharging at Solfatara affect the infiltration and propagation of meteoric water through porous rock and fractures, in turn influencing the poroelastic response of the volcanic system. As a result, Campi Flegrei caldera, differently from Vesuvius, is prone to respond to the stress variations related to pore-fluid pressure changes.

Finally, besides the medium properties and the presence of an active shallow hydrothermal system, a further factor which can control the response to rain-induced hydrological variations is the state of the volcano. Vesuvius is characterized by a low-level background activity, poorly influenced by external forcing. On the contrary, at Campi Flegrei endogenous processes related to the ongoing unrest likely drive the system towards metastable conditions. Although the rain-induced deformation is two orders of magnitude lower than that related to the volcanic uplift, we can reasonably infer that rainfall can have an impact in modulating the dynamics of such a metastable system, which is more sensitive to exogenous triggering (Petrosino et al., 2018).

The present outcomes are the first steps for the future development of a finer modeling of water load and diffusive processes related to rainfall phenomena. Additional factors such as duration and intensity of the precipitations, pre-rainfall moisture conditions of the soil, rock physical parameters (fracture density, porosity, permeability) and threshold non linear mechanisms (Yamauchi 1987; Dal Moro and Zadro, 1998) should be eventually taken into account with the ultimate goal to determine a more accurate as possible transfer function between rainfall and ground response and seismicity.

DATA AVAILABILITY STATEMENT

The dataset of the daily RMS of the ground tilt at Vesuvius and Campi Flegrei can be found in the Zenodo repository https://doi.org/10.5281/zenodo.5196688. The INGV-OV seismic catalogue is available at the https://www.ov.ingv.it/index.php/cataloghi-sismici-vulcani-napoletani?category[0]=73&category_children=1&own=0. Rainfall amount data were downloaded by the historical archive of the website https://www.3bmeteo.com/meteo/ora/storico.

AUTHOR CONTRIBUTIONS

SP and CR conceived the research study, analyzed data and interpreted the results. IA handled the processing of raw tiltmeter data and drew **Figure 1**. SP wrote the first draft; all the authors read, corrected and approved the final article.

FUNDING

This work is part of the INGV research project LAST: Linked Analysis of Seismic and Tiltmeter observables (Ricerca Libera 2019 - Funding n. 53/2020). Publication fee has been supported by the “Institutional Funding for Editorial Activity” of INGV, Sezione di Napoli - Osservatorio Vesuviano.

ACKNOWLEDGMENTS

We acknowledged the INGV-OV Seismic Laboratory for having compiled the earthquake catalogue, and the INGV-OV Laboratory of Geomatics and Thermography (LGT) for having provided the base maps of **Figure 1**. We wish to thank Vincenzo Augusti for providing regular maintenance of the tiltmeter networks. Two reviewers are acknowledged for their suggestions, which improved the clarity of the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.758602/full#supplementary-material

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