On the Link Between Global Volcanic Activity and Global Mean Sea Level

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Studying a large number of volcanic eruptions is a way to decipher general characteristics related to volcano dynamics but also on external forcing influencing it, such as solid Earth and ocean tides. Many studies have tackled this tidal influence on the onset of volcanic eruptions and more generally, on volcanic activity. However, the interplay between this quasi-permanent forcing and volcanic systems is still poorly understood. With the present study, we propose to consider a global viewpoint to address this interaction. We analyzed the number of monthly volcanic eruptions and the global mean sea level between 1880 and 2009 using the Singular Spectrum Analysis time-series analysis technique to evaluate the existence of common periodicities. We found multi-decadal components of similar periodicities present in both time-series which we link to those already recognized in the polar motion. Its multi-decadal variations result in a mass reorganization in the oceans whose associated stress changes may impact processes generating volcanic eruptions worldwide. Our results show the influence of global processes on volcanic activity and open many questions to further investigate these multi-scale interactions.

Keywords: external forcing, volcanic activity, global mean sea level, solid Earth and ocean tides, eruption triggering, interaction external/internal processes, singular spectrum analysis, polar motion

INTRODUCTION

The triggering of volcanic eruptions represents the ultimate stage of a series of non-linear physico-chemical processes. Although the conditions that make a volcano ready to enter in eruption are still elusive, deciphering those that participate in the destabilization of metastable systems could provide new insights on the processes leading to eruption triggering. Knowledge of how volcanic systems work has been mainly gained from studies on individual volcanoes first based on specific methodologies and more and more on multi-method approaches (e.g., McNutt, 1996; Newhall and Punongbayan, 1996; Battaglia et al., 2006; Dzurisin, 2006; Sigmundsson et al., 2015; Gudmundsson et al., 2016). Despite of the high variability of volcanoes illustrated in particular by their eruptive activity, internal structure, or chemical composition, common processes drive volcanic activity (Cashman and Biggs, 2014). Studies on a large number of volcanoes have allowed to provide more constraints on global processes controlling their dynamics and evolution as for instance, the magnitude-frequency relationship of large explosive eruptions (e.g., Deligne et al., 2010), the link between deformation and eruption (e.g., Biggs et al., 2014), as well as the role of external forcing on the eruption triggering such as tectonic earthquakes (Seropian et al., 2021), the sea level and climate variations (e.g., Laskar et al., 2004; Mason et al., 2004; Kutterolf et al., 2013; Satow et al., 2021) and Earth tides (Mauk and Jonhston, 1973).

Actually, the variations of the sea level, climate and Earth tides are all related, taking part of a global dynamics as pieces of a giant puzzle. The Liouville-Euler equations link the redistribution of

mass at Earth's surface, and in particular that of the fluid envelopes to the movement of the Earth's rotation axis through a system of linear equations and excitation functions (Lambeck, 2005; Lopes et al., 2021). These movements take place at different time scales ranging from a few days to at least 18.6 years, as revealed by the study of the length-of-day variations, a global parameter whose fluctuations on short-term capture the mass redistribution on Earth through their impact on Earth's rotation velocity (Le Mouël et al., 2019). The revolution of the Earth around the Sun and the variations of the Earth's rotation axis that are associated with seasons and Milankovitch cycles modulate this force and mass movements and interfere with those induced by plate tectonics, ocean and atmospheric currents (e.g., Lambeck, 2005; Le Mouël et al., 2021a,b; Zaccagnino et al., 2020).

The idea of tidal influence on volcanic activity has persisted over the last century (e.g., Jaggar et al., 1924; McNutt and Beavan, 1987; Emter 1997; Sottili et al., 2021). Statistical approaches have shown that the onset of volcanic eruptions at global scale (e.g., Mauk and Johnston, 1973) as well as at local scale (e.g., Johnston and Mauk, 1972; Filson et al., 1973; Golombek and Carr, 1978; Dzurizin, 1980; Martin and Rose, 1981) could be related to the Moon and in particular, its alignment with the Earth and the Sun, known as the fortnightly cycle. Similar observations of preferred periods for eruption onsets have been made with ocean tides for submarine, coastal and insular volcanic systems (e.g., McNutt and Beavan, 1987; McNutt, 1999; Mason et al., 2004; Tolstoy, 2015). In coastal environment, the tidal deformation coupled with the ocean loading, which corresponds to the movement of surface water mass, induce variations in the compressional stresses that can promote squeezing out magma (e.g., McNutt and Beavan, 1987; McNutt, 1999). At time scales of hundreds of thousands years, pronounced sea level variations related to ice melting and more generally long-period climatic and astronomical variations have also been associated with pulses of volcanic activity, e.g., Mason et al. (2004); Andrew and Gudmundsson (2007); Pagli and Sigmundsson (2008); Kutterolf et al. (2013); Watt et al. (2013); Satow et al. (2021); Sottili et al. (2021).

The influence of solid Earth and ocean tides has also been suggested on shorter time scales through periodic behavior detected in various physical parameters measured at volcanoes, e.g., seismic tremor, earthquake rate, gas fluxes. Actually, tidal constituents have been identified at volcanoes independently of their phases of activity including quiescence, unrest and eruptions (e.g., Jaggar et al., 1924; McNutt and Beavan, 1981, 1984; Shimozuru, 1987; Leandro and Alvarado 1988; Rydelek et al., 1988; Caltabanio et al., 1994; Kasahara et al., 2001; Custódio et al., 2003; López et al., 2006; Roult et al., 2012; Sottili and Palladino, 2012; Yakiwara et al., 2013; Bredemeyer and Hesteen, 2014; Conde et al., 2014; Contadakis et al., 2017; Dinger et al., 2018; Girona et al., 2018; Patrick et al., 2019; Dumont et al., 2020, 2021; İçhedef et al., 2020; Miguelsanz et al., 2021). Most of these parameters express the transfer of fluids, either melt or/and hydrothermal fluids, from deeper layers towards and at the Earth's surface. At the quiescent and hydrothermally active caldera of Campi Flegrei (Italy), studies have demonstrated

that tidal modulation can take place according to a complex coupling mechanism that affects both crustal structure and hydrothermal fluids (e.g., Bottiglieri et al., 2010; De Lauro et al., 2012, 2013, 2018; Petrosino et al., 2018, 2020; Ricco et al., 2019; Caputo et al., 2020; Cusano et al., 2021; Petrosino and Dumont, 2022). At erupting volcanoes, increase in explosions or seismic activity as well as second-order variations of geophysical time-series were also attributed to tides (e.g., Mauk and Kienle, 1973; Golombek and Carr, 1978; Martin and Rose, 1981; Jentzsch et al., 2001; Williams-Jones et al., 2001; Dumont et al., 2020, 2021).
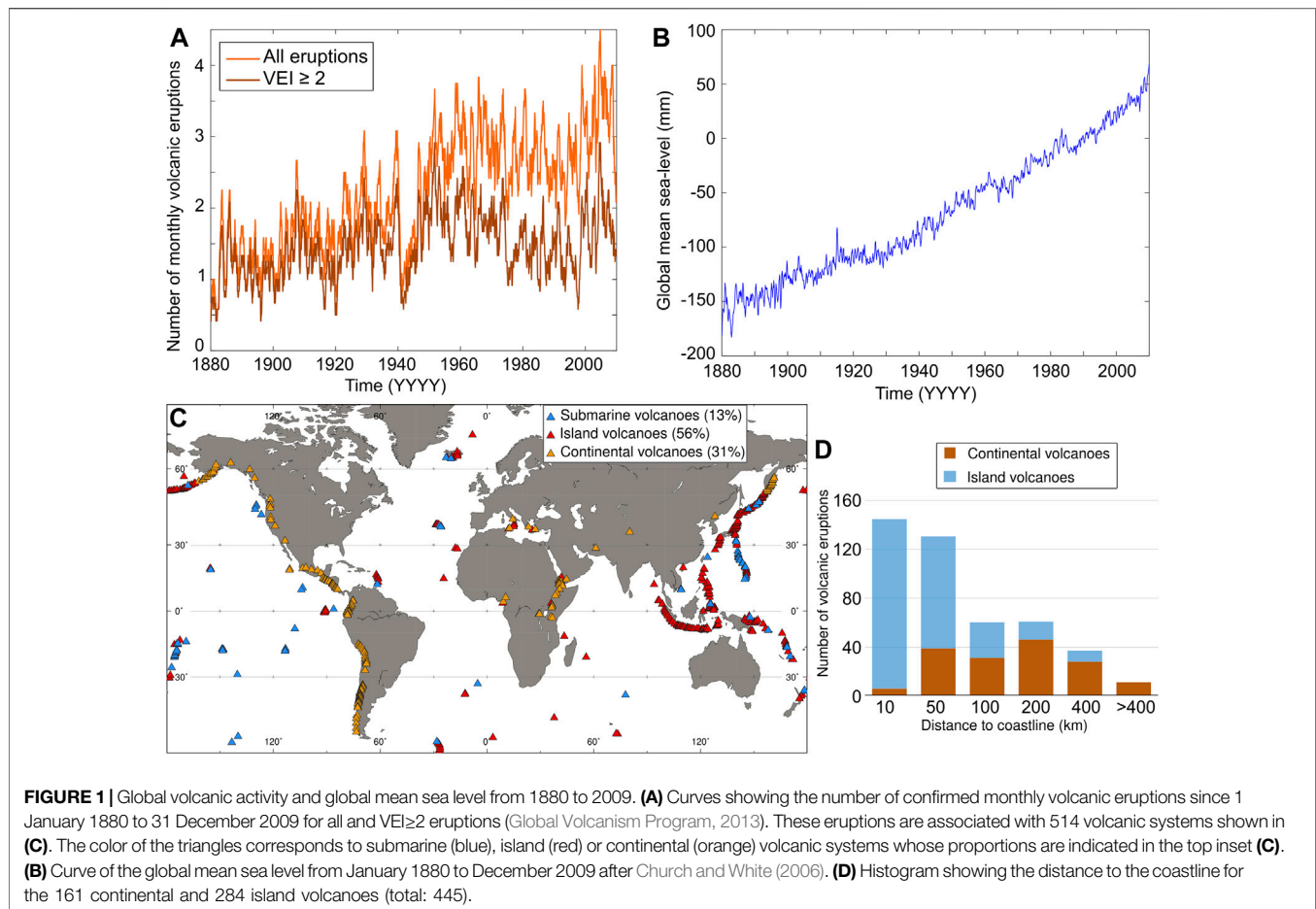
Despite all these observations, not all volcanoes show a sensitivity to solid Earth and ocean tides, and the cause-effect relationship is still elusive (e.g., Sparks, 1981; Neuberg, 2000). Actually, past studies have mainly focused either on short or very-long time scales, from hours to a few years on one hand, or over several kyr on the other hand. However, the interaction between tidally-generated movements and volcanic systems is expected to occur on all time scales on which this external forcing acts. Therefore, should we not expect a possible response of volcanoes at all these time-scales?

We address these questions by exploring the link between ocean tides and volcanoes from a global viewpoint over a ~130 years time interval. Oceans as all fluid and solid envelopes on Earth respond to external forcing induced by lunisolar tidal potential. They participate in a significant redistribution of mass through ocean loading, and therefore stresses at Earth's surface over different time scales. Considering that most volcanoes lie near, within or beneath the oceans (**Figure 1**), we can raise the question of whether the tidally-induced ocean movements and therefore stresses can participate in changing the dynamical systems and so the destabilization of volcanoes on decadal timescales. This is what we tackle with this paper, by analyzing the common periodicities which may exist in the number of worldwide volcanic eruptions and the global mean sea level using the Singular Spectrum Analysis (SSA) technique.

INVESTIGATING THE LINK BETWEEN THE GLOBAL MEAN SEA LEVEL AND WORLDWIDE VOLCANIC ACTIVITY
Data and Method

We considered volcanic eruptions worldwide reported by the Smithsonian Institution through the Global Volcanism Program (2013) spanning a 129-year period from 1 January 1880 to 31 December 2009. This data series counts 3,781 confirmed eruptions with known Volcanic Explosivity Index (VEI, Newhall and Self, 1982), associated to 514 volcanic systems (**Figure 1C**). We built a number of volcanic eruptions (NVE) using a median filter with a 12-months sliding window applied to the number of monthly eruptive events (**Figure 1A**). We performed a similar analysis for eruptions with VEI≥2 to test the stability of our results with respect to the catalog completeness. We also classified these volcanic systems according to their environment, i.e. continental, insular or

FIGURE 1 | Global volcanic activity and global mean sea level from 1880 to 2009. **(A)** Curves showing the number of confirmed monthly volcanic eruptions since 1 January 1880 to 31 December 2009 for all and VEI≥2 eruptions (Global Volcanism Program, 2013). These eruptions are associated with 514 volcanic systems shown in **(C)**. The color of the triangles corresponds to submarine (blue), island (red) or continental (orange) volcanic systems whose proportions are indicated in the top inset **(C)**. **(B)** Curve of the global mean sea level from January 1880 to December 2009 after Church and White (2006). **(D)** Histogram showing the distance to the coastline for the 161 continental and 284 island volcanoes (total: 445).

submarine, and for the first two settings, we calculated their distance to the coastline (**Figures 1C,D**, **Supplementary Figure S1**).

We used the reconstruction of the Global Mean Sea Level (GMSL) by Church and White (2006). The GMSL time-series is derived from data acquired from both worldwide-distributed tide gauges and different altimeter satellites. It has a monthly-sampling which was only corrected for Glacial Isostatic Adjustment (**Figure 1B**).

We analyzed both time-series, e.g. that of volcanic eruptions and that of GMSL, using SSA. This technique has been widely applied on various geophysical data sets (Carniel et al., 2006; Bozzo et al., 2010; Lopes et al., 2021; Dumont et al., 2020, 2021; Petrosino and Dumont, 2022), including sea level (Le Mouël et al., 2021a,b). This time-series analysis technique allows to decompose any time-series into a sum of physical components corresponding to slowly-varying components such as trend, regular and modulated oscillations and noise (e.g., Golyandina and Zhigljavsky, 2013). First, the cross-lagged correlation matrix was built from embedded vectors of lengths adapted to each time-series [561 for GMSL, 2,682 for NVE (all eruptions) and 1,416 for NVE (VEI≥2)]. Then, the singular value decomposition was applied resulting in eigenvectors and eigenvalues that were identified as non- or pseudo-oscillatory components and

whose periods were estimated using Fourier Transform. We only considered the first five eigenvalues which are the strongest components of the original signal (**Supplementary Figure S2**).

Results

The number of reported volcanic eruptions increases over the whole time interval (**Figure 1A**), which does not represent a global increase of volcanic activity on Earth but rather more systematic reports on eruptions around the world over the 20th century. A significant drop appears, around 1940, due to the second world war, followed by a sharp increase up to ~1950–1960. Then, the period ~1960- late 1990 was characterized by a slow decrease of volcanic activity which preceded a strong increase that culminated around 2005. Very similar variations are observed for VEI≥2 eruptions. Over the 1880–2009 period, the variations of the GMSL (**Figure 1B**) appear more regular, with a global increase of ~2 cm punctuated by shorter variations of low amplitude (<0.5 cm).

Three of the first five eigenvalues of the NVE (all eruptions and VEI≥2) appear to be very similar, and within uncertainties, to those detected in the GMSL (**Figure 2** and **Supplementary Figures S2, S3**). They are characterized by a period of 52.5 years, 37.9 ± 8.9 years and 19.8 ± 2.2 years (56.9 ± 20.4 years,
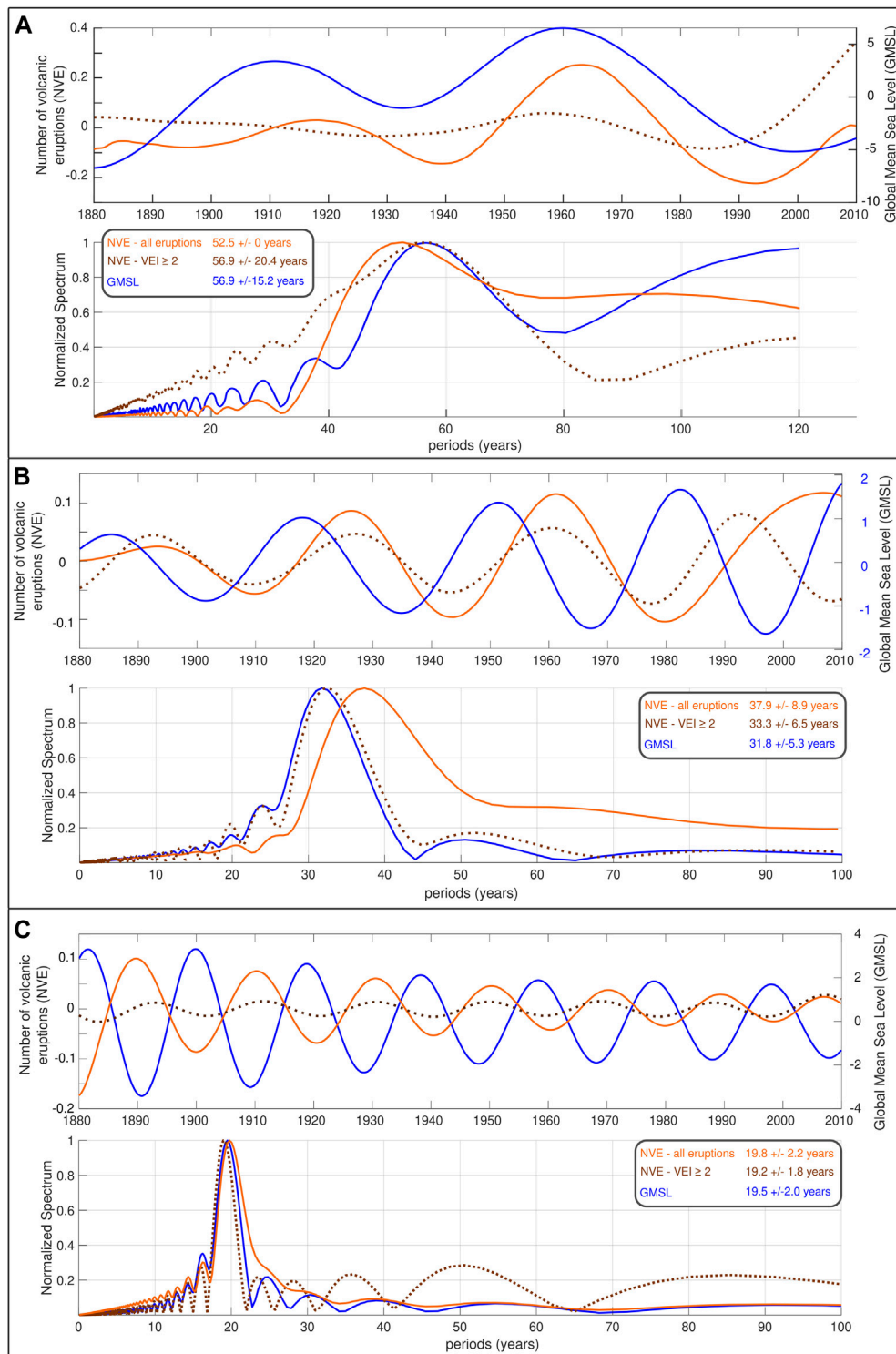
FIGURE 2 | Examples of common long-period components extracted using SSA in the global mean sea level (blue) and volcanism (orange for all eruptions and dotted brown for VEI≥2 eruptions) with that of **(A)** ~50–60, **(B)**~30, and **(C)** ~20 years.

33.3 ± 6.5 years and 19.2 ± 1.8 years for VEI≥2). The corresponding periods extracted in the GMSL are of 56.9 ± 15.2 years, 31.8 ± 5.3 years and 19.5 ± 2 years. To further

investigate their link, we compare their waveforms (**Figure 2**). The first periodicity of ~50–60 years appears in phase for the NVE and GSML although the uncertainties are relatively

significant. Thus, when the global mean sea level is high, the volcanic activity is also globally high on Earth. For the ~20-year components, the NVE and GMSL appear in phase opposition, while for the ~30 years a phase delay is detected between GMSL variations and volcanic activity. In the NVE, we also found a component of ~85 years (~90 years for VEI≥2) that is not well resolved due to the duration of the time interval considered. Although not found in the GMSL analyzed in this paper, previous studies of sea level data have found a similar cycle of ~90 years, known also as the Gleissberg cycle (cf. Gleissberg, 1939; Le Mouël et al., 2021b).

DISCUSSION

Our analysis, performed for both the whole eruption catalog and VEI≥2 eruptions, shows the existence of consistent multi-decadal periodicities not only for low and non-explosive eruptions but also for explosive-dominated phenomena as already suggested for sulfur rich tropical eruptions (Ammann and Nadeau, 2003), and despite a catalog completeness which has kept improving over the 20th century (Siebert et al., 2015). Although some of the uncertainties are significant, very comparable periodicities were found in the GMSL. These different periodicities form the larger contributions in each time-series representing more than 90% of the original signals, once considered together with the trend (**Supplementary Figures S2, S3, S4**). Moreover, a specific link between these multi-decadal components extracted in the NVE and GMSL is observed (in phase, phase shifted/opposition). All together, these results lead us to consider that these multi-decadal periodicities in the NVE and GMSL time-series are related.

Most volcanic eruptions considered in this study, e.g. ~70%, occur on volcanoes located either on islands or sea floor, indicating a prime link of spatial order between volcanic systems and oceans, knowing that the submarine eruptions are by far underestimated (**Figures 1C,D**). Moreover, for volcanoes situated on continents or islands, about 54% of them are located within 50 km to the coast (**Figure 1D**, **Supplementary Figure S1**). Water, which is ubiquitous on Earth, is not only present at Earth's surface but also as groundwater, penetrating beneath the islands and far into the continents. Water also accumulates within intraplate regions (e.g., Gleeson et al., 2016; Craig et al., 2017; MacMillan et al., 2019; Jasechko et al., 2020). All fluid layers redistribute water masses from the microscopic scale through pore-fluid pressures to the global scale via their loading, by oscillating at periods ranging from few hours to multi-decades in response to tidal forces and pole motion (e.g., Lambeck, 2005; MacMillan et al., 2019; Le Mouël et al., 2021b; Lopes et al., 2021). These two different ways by which water can interfere with dynamical systems have not only been suggested for volcanoes, but also for fault systems where tidal stresses may enhance the long-term tectonic loads (Thomas et al., 2009; Neves et al., 2015; Ide et al., 2016). Considering that both faults and volcanoes share some commonalities in their driving processes, we believe that taking into account their response to external forcing could improve understanding of how this interplay works.

Past studies spotted that long periods (>6 months) of the hydrological cycle can influence eruption onsets at volcanoes located nearby the coast (e.g., McNutt and Beavan, 1987; McNutt, 1999). This idea seems to be confirmed by our study and the work of Mason et al. (2004) based on worldwide catalog of eruptions who showed a correlation between eruption rates and annual sea level variations. Besides, it is well known that bathymetry and boundary effects associated with coastlines have a major impact on the local amplitudes of semi-diurnal, spring, and neap tides (**Supplementary Figure S5**). Likewise, sea level variations over longer time scales, like the ones highlighted in this study, have different amplitudes and larger loading depending on geographic location. As long periods of hydrological loading redistribute more water masses than shorter periods, it could explain why long periods and multi-decadal periodicities would have more impact on unstable and dynamical systems.

Detecting these decadal periodicities in both time-series suggests as well that they relate to a global phenomenon. Although the way these processes take place and interfere is still puzzling, we note that four similar multi-decadal periods were detected in the fluctuations of the pole motion, being of 21.6, 31.5, 57.3 and 92.2 years (e.g., Lopes et al., 2021). Yet, any movement of the Earth's rotation axis is accompanied by mass movements according to Liouville-Euler equations (Lambeck, 2005; Lopes et al., 2021). This may be illustrated by the late Pleistocene deglaciation, the concomitant sea level changes and a secular drift present in the pole motion (Nakiboglu and Lambeck, 1980). This is what we observe through the common periodicities extracted in the GMSL and the pole motion (Lopes et al., 2021). We interpret the presence of these decadal periodicities in the NVE as a consequence of this global mass redistribution operating at similar time scales. The water masses transported over these decadal periods induce pressure changes on crust that adds to the local stresses, leading to a slow destabilization of magma plumbing systems. In fact, the decadal cycles extracted in the NVE do not properly trigger one eruption every ~50 or ~20 years as evidenced by the amplitude of the waveforms extracted by SSA (**Figure 2**), although they participate to the triggering process. Complementary approaches will be necessary for better understanding this link, as for instance, numerical modeling to investigate how tidal stresses can destabilize magma chambers and fault systems (McNutt and Beaven, 1987; Ide et al., 2016; Jonhson et al., 2017; Scholz, 2019). Moreover, the impact of the fluctuations of the Earth's rotation axis on volcanic eruptions was also suggested locally and regionally (Kutterolf et al., 2013; Lambert and Sottili, 2019).

CONCLUDING REMARKS AND FUTURE PERSPECTIVES

Our study leads us to suggest that movements affecting globally our planet over a wide range of time scales, e.g., lunisolar gravitational forces, pole motion, may contribute to the dynamics of volcanic systems. These considerations and results raise also some more questions as for instance, are volcanoes sensitive to all or just some of these periodicities and what may

explain these differences? Could this forcing be viewed as a background variation participating in the regular dynamics of magma plumbing systems? We think that these decadal variations together with short and very long periodicities deserve to be more explored and investigated as they might reveal global conditions and space-time patterns favorable to eruption triggering.

These results represent an avenue to explore how the mass redistribution acting at global scale participates in the processes leading to the triggering of volcanic eruptions as already suggested by Mason et al. (2004) or Sottili et al. (2021). Deciphering the link between global and local scale is critical to understand how external forcing acts on different time scales and how it can disrupt dynamical systems like volcanoes. We think that assessing these processes at multiple scales will allow to provide more constraints on the parameters and conditions that make volcanoes sensitive to small environmental changes (e.g. Canon-Tapia, 2014; Caricchi et al., 2021).

Singular Spectrum Analysis, in addition to be a robust time-series analysis technique that has been applied to a large variety of Earth sciences data, allows to extract trends and periodic components without an a priori model, which has some advantages when analyzing signals integrated at various time scales such as tides and whose modulation may vary over time as in case of seismic tremor in a highly heterogeneous medium (e.g., Petrosino and Dumont, 2022). Similar analyses could provide new insights on studied processes, including cause-effect relationships between parameters as well as what makes some volcanoes sensitive to quasi-permanent external forcing and why (e.g., Dumont et al., 2021). All active volcanoes do not respond to solid Earth and ocean tides (e.g., Neuberg, 2000) and that sensitivity may be related to inherent properties of volcanoes, their location on Earth or the plate boundaries conditions (e.g., Mauk and Johnston, 1973; Dzurisin, 1980; Dumont et al., 2021). Many studies have also reported an increase of the sensitivity to tidal forcing when plumbing systems are approaching a critical state coinciding for some volcanoes to pre-eruptive periods (e.g., Filson et al., 1973; Berrino and Corrado, 1991; De Lauro et al., 2013; Girona et al., 2018; Miguelsanz et al., 2021). More systematics observations are required to unravel these critical conditions.

Technique plays an important role in the road to findings, but data, as all the ingredients in a recipe, play an equally fundamental role. The data availability and quality are of great importance to advance in the comprehension of the interplay between external and internal processes at volcanoes. The role of volcano observatories and initiatives such WOVOdat (Newhall et al., 2017) or the Global Volcanism Program (2013) have been primordial to tackle these questions and many others. Revisiting past volcanic activity together with recent volcanic events, from global to local scale using time-series analysis, may help to advance in this direction.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. The list of worldwide volcanic eruptions is from the Global Volcanism Program, Smithsonian Institution (Global Volcanism Program, 2013): https://volcano.si.edu/. The global mean sea-level data from Church and White (2006) is accessible here: https://www.psmsl.org/products/reconstructions/church.php.

AUTHOR CONTRIBUTIONS

SD contributed to conceptualization, data analysis and led the writing of the original draft. SD and MN made the figures. All authors contributed to the writing, review and editing of the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.845511/full#supplementary-material

REFERENCES

Ammann, C. M., and Naveau, P. (2003). Statistical Analysis of Tropical Explosive Volcanism Occurrences over the Last 6 Centuries. *Geophys. Res. Lett.* 30 (5), 1210. doi:10.1029/2002gl016388

Andrew, R. E., and Gudmundsson, A. (2007). Distribution, Structure, and Formation of Holocene Lava Shields in Iceland. *J. Volcanol. Geotherm. Res.* 168 (1-4), 137–154. doi:10.1016/j.jvolgeores.2007.08.011

Battaglia, M., Troise, C., Obrizzo, F., Pingue, F., and De Natale, G. (2006). Evidence for Fluid Migration as the Source of Deformation at Campi Flegrei Caldera (Italy). *Geophys. Res. Lett.* 33 (1), L01307. doi:10.1029/2005gl024904

Berrino, G., and Corrado, G. (1991). Tidal Signal in the Recent Dynamics of Campi Flegrei Caldera (Italy). *J. Volcanol. Geotherm. Res.* 48 (1-2), 93–101. doi:10.1016/0377-0273(91)90035-x

Biggs, J., Ebmeier, S. K., Aspinall, W. P., Lu, Z., Pritchard, M. E., Sparks, R. S., et al. (2014). Global Link between Deformation and Volcanic Eruption Quantified by Satellite Imagery. *Nat. Commun.* 5 (1), 3471–3477. doi:10.1038/ncomms4471

Bottiglieri, M., Falanga, M., Tammaro, U., De Martino, P., Obrizzo, F., Godano, C., et al. (2010). Characterization of GPS Time Series at the Neapolitan Volcanic Area by Statistical Analysis. *J. Geophys. Res. Solid Earth* 115 (B10), B10416. doi:10.1029/2009jb006594

Bozzo, E., Carniel, R., and Fasino, D. (2010). Relationship between Singular Spectrum Analysis and Fourier Analysis: Theory and Application to the Monitoring of Volcanic Activity. *Comput. Math. Appl.* 60 (3), 812–820. doi:10.1016/j.camwa.2010.05.028

Bredemeyer, S., and Hansteen, T. H. (2014). Synchronous Degassing Patterns of the Neighbouring Volcanoes Llaima and Villarrica in South-Central Chile: the Influence of Tidal Forces. *Int. J. Earth Sci. Geol. Rundsch)* 103 (7), 1999–2012. doi:10.1007/s00531-014-1029-2

Caltabiano, T., Romano, R., and Budetta, G. (1994). SO2flux Measurements at Mount Etna (Sicily). *J. Geophys. Res.* 99 (D6), 12809. doi:10.1029/94jd00224

Cañón-Tapia, E. (2014). Volcanic Eruption Triggers: A Hierarchical Classification. *Earth-Science Rev.* 129, 100–119. doi:10.1016/j.earscirev.2013.11.011

Caputo, T., Cusano, P., Petrosino, S., Sansivero, F., and Vilardo, G. (2020). Spectral Analysis of Ground Thermal Image Temperatures: what We Are Learning at Solfatara Volcano (Italy). *Adv. Geosci.* 52, 55–65. doi:10.5194/adgeo-52-55-2020

Caricchi, L., Townsend, M., Rivalta, E., and Namiki, A. (2021). The Build-Up and Triggers of Volcanic Eruptions. *Nat. Rev. Earth Environ.* 2, 458–476. doi:10.1038/s43017-021-00174-8

Carniel, R., Barazza, F., Tárraga, M., and Ortiz, R. (2006). On the Singular Values Decoupling in the Singular Spectrum Analysis of Volcanic Tremor at Stromboli. *Nat. Hazards Earth Syst. Sci.* 6 (6), 903–909. doi:10.5194/nhess-6-903-2006

Cashman, K., and Biggs, J. (2014). Common Processes at Unique Volcanoes—a Volcanological Conundrum. *Front. Earth Sci.* 2, 28. doi:10.3389/feart.2014.00028

Church, J. A., and White, N. J. (2006). A 20th Century Acceleration in Global Sea-level Rise. *Geophys. Res. Lett.* 33 (1), L01602. doi:10.1029/2005gl024826

Conde, V., Bredemeyer, S., Duarte, E., Pacheco, J. F., Miranda, S., Galle, B., et al. (2014). SO2 Degassing from Turrialba Volcano Linked to Seismic Signatures during the Period 2008-2012. *Int. J. Earth Sci. Geol. Rundsch)* 103 (7), 1983–1998. doi:10.1007/s00531-013-0958-5

Contadakis, M. E., Arabelos, D. N., and Vergos, G. (2017). Testing the Recent Santorini Seismic Activity for Possible Tidal Triggering Effect. *geosociety* 51, 1–17. doi:10.12681/bgsg.11653

Craig, T. J., Chanard, K., and Calais, E. (2017). Hydrologically-driven Crustal Stresses and Seismicity in the New Madrid Seismic Zone. *Nat. Commun.* 8 (1), 2143–2211. doi:10.1038/s41467-017-01696-w

Cusano, P., Caputo, T., De Lauro, E., Falanga, M., Petrosino, S., Sansivero, F., et al. (2021). Tracking the Endogenous Dynamics of the Solfatara Volcano (Campi Flegrei, Italy) through the Analysis of Ground Thermal Image Temperatures. *Atmosphere* 12 (8), 940.

Custodio, S. I., Fonseca, J. F., d'Oreye, N. F., Faria, B. V., and Bandomo, Z. (2003). Tidal Modulation of Seismic Noise and Volcanic Tremor. *Geophys. Res. Lett.* 30 (15), 1816. doi:10.1029/2003gl016991

De Lauro, E., De Martino, S., Falanga, M., and Petrosino, S. (2013). Synchronization between Tides and Sustained Oscillations of the Hydrothermal System of Campi Flegrei (Italy). *Geochem. Geophys. Geosyst.* 14 (8), 2628–2637. doi:10.1002/ggge.20149

De Lauro, E., Falanga, M., and Petrosino, S. (2012). Study on the Long-Period Source Mechanism at Campi Flegrei (Italy) by a Multi-Parametric Analysis. *Phys. Earth Planet. Interiors* 206, 16–30.

De Lauro, E., Petrosino, S., Ricco, C., Aquino, I., and Falanga, M. (2018). Medium and Long Period Ground Oscillatory Pattern Inferred by Borehole Tiltmetric Data: New Perspectives for the Campi Flegrei Caldera Crustal Dynamics. *Earth Planet. Sci. Lett.* 504, 21–29. doi:10.1016/j.epsl.2018.09.039

Deligne, N. I., Coles, S. G., and Sparks, R. S. J. (2010). Recurrence Rates of Large Explosive Volcanic Eruptions. *J. Geophys. Res. Solid Earth* 115 (B6), B06203. doi:10.1029/2009jb006554

Dinger, F., Bobrowski, N., Warnach, S., Bredemeyer, S., Hidalgo, S., Arellano, S., et al. (2018). Periodicity in the BrO/SO_2 Molar Ratios in the Volcanic Gas Plume of Cotopaxi and its Correlation with the Earth Tides during the Eruption in 2015. *Solid earth* 9 (2), 247–266. doi:10.5194/se-9-247-2018

Dumont, S., Le Mouël, J.-L., Courtillot, V., Lopes, F., Sigmundsson, F., Coppola, D., et al. (2020). The Dynamics of a Long-Lasting Effusive Eruption Modulated by Earth Tides. *Earth Planet. Sci. Lett.* 536, 116145. doi:10.1016/j.epsl.2020.116145

Dumont, S., Silveira, G., Custódio, S., Lopes, F., Le Mouël, J.-L., Gouhier, M., et al. (2021). Response of Fogo Volcano (Cape Verde) to Lunisolar Gravitational Forces during the 2014-2015 Eruption. *Phys. Earth Planet. Interiors* 312, 106659. doi:10.1016/j.pepi.2021.106659

Dzurisin, D. (1980). Influence of Fortnightly Earth Tides at Kilauea Volcano, Hawaii. *Geophys. Res. Lett.* 7 (11), 925–928. doi:10.1029/gl007i011p00925

Dzurisin, D. (2006). *Volcano Deformation: New Geodetic Monitoring Techniques.* Berlin: Springer Science & Business Media.

Emter, D. (1997). *Tidal Triggering of Earthquakes and Volcanic Events.* Berlin, Heidelberg: Tidal phenomena, 293–309.

Filson, J., Simkin, T., and Leu, L.-k. (1973). Seismicity of a Caldera Collapse: Galapagos Islands 1968. *J. Geophys. Res.* 78 (35), 8591–8622. doi:10.1029/jb078i035p08591

Girona, T., Huber, C., and Caudron, C. (2018). Sensitivity to Lunar Cycles Prior to the 2007 Eruption of Ruapehu Volcano. *Sci. Rep.* 8 (1), 1476. doi:10.1038/s41598-018-19307-z

Gleeson, T., Befus, K. M., Jasechko, S., Luijendijk, E., and Cardenas, M. B. (2016). The Global Volume and Distribution of Modern Groundwater. *Nat. Geosci.* 9 (2), 161–167. doi:10.1038/ngeo2590

Gleissberg, W. (1939). A Long-Periodic Fluctuation of the Sun-Spot Numbers. *Observatory* 62, 158–159.

Global Volcanism Program (2013). in *Volcanoes of the World, V. 4.9.2 (15 Dec 2020).* Editor E Venzke (United States: Smithsonian Institution). doi:10.5479/si.GVP.VOTW4-2013

Golombek, M. P., and Carr, M. J. (1978). Tidal Triggering of Seismic and Volcanic Phenomena during the 1879–1880 Eruption of Islas Quemadas Volcano in El Salvador, Central America. *J. Volcanol. Geotherm. Res* 3 (3–4), 299–307. doi:10.1016/0377-0273(78)90040-9

Golyandina, N., and Zhigljavsky, A. (20132013). *Singular Spectrum Analysis for Time Series.* Berlin, Heidelberg: Springer.

Gudmundsson, M. T., Jónsdóttir, K., Hooper, A., Holohan, E. P., Halldórsson, S. A., Ófeigsson, B. G., et al. (2016). Gradual Caldera Collapse at Bárdarbunga Volcano, Iceland, Regulated by Lateral Magma Outflow. *Science* 353 (6296), aaf8988. doi:10.1126/science.aaf8988

İçhedef, M., Giammanco, S., Neri, M., Catalano, R., Immé, G., Morelli, D., et al. (2020). In Soil Radon Anomalies and Volcanic Activity on Mt. Etna (Italy). *J. Environ. Radioact.* 218, 106267. doi:10.1016/j.jenvrad.2020.106267

Ide, S., Yabe, S., and Tanaka, Y. (2016). Earthquake Potential Revealed by Tidal Influence on Earthquake Size-Frequency Statistics. *Nat. Geosci.* 9 (11), 834–837. doi:10.1038/ngeo2796

Jaggar, T. A., Finch, R. H., and Emerson, O. H. (1924). The Lava Tide, Seasonal Tilt, and the Volcanic Cycle. *Mon. Wea. Rev.* 52 (3), 142–145. doi:10.1175/1520-0493(1924)52<142:tltsta>2.0.co;2

Jasechko, S., Perrone, D., Seybold, H., Fan, Y., and Kirchner, J. W. (2020). Groundwater Level Observations in 250,000 Coastal US Wells Reveal Scope

of Potential Seawater Intrusion. *Nat. Commun.* 11 (1), 3229–9. doi:10.1038/s41467-020-17038-2

Jentzsch, G., Haase, O., Kroner, C., and Winter, U. (2001). Mayon Volcano, Philippines: Some Insights into Stress Balance. *J. Volcanol. Geotherm. Res.* 109 (1-3), 205–217. doi:10.1016/s0377-0273(00)00312-7

Johnson, C. W., Fu, Y., and Bürgmann, R. (2017). Stress Models of The Annual Hydrospheric, Atmospheric, Thermal, and Tidal Loading Cycles on California Faults: Perturbation of Background Stress and Changes in Seismicity. *J. Geophys. Res.: Solid Earth* 122 (12), 10-605.

Johnston, M. J. S., and Mauk, F. J. (1972). Earth Tides and the Triggering of Eruptions from Mt Stromboli, Italy. *Nature* 239 (5370), 266–267. doi:10.1038/239266b0

Kasahara, J., Nakao, S., and Koketsu, K. (2001). Tidal Influence on the 2000 Miyake Jima Eruption and its Implications for Hydrothermal Activity and Volcanism. *Proc. Jpn. Acad. Ser. B Phys. Biol. Sci.* 77 (6), 98–103. doi:10.2183/pjab.77.98

Kutterolf, S., Jegen, M., Mitrovica, J. X., Kwasnitschka, T., Freundt, A., and Huybers, P. J. (2013). A Detection of Milankovitch Frequencies in Global Volcanic Activity. *Geology* 41 (2), 227–230. doi:10.1130/g33419.1

Lambeck, K. (2005). *The Earth's Variable Rotation: Geophysical Causes and Consequences.* Cambridge: Cambridge University Press.

Lambert, S., and Sottili, G. (2019). Is There an Influence of the Pole Tide on Volcanism? Insights from Mount Etna Recent Activity. *Geophys. Res. Lett.* 46 (23), 13730–13736. doi:10.1029/2019gl085525

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., and Levrard, B. (2004). A Long-Term Numerical Solution for the Insolation Quantities of the Earth. *A&A* 428 (1), 261–285. doi:10.1051/0004-6361:20041335

Le Mouël, J. L., Lopes, F., and Courtillot, V. (2021a). A Strong Link between Variations in Sea-Ice Extent and Global Atmospheric Pressure? *The Cryosphere Discussions*, 1–28. doi:10.5194/tc-2021-216

Le Mouël, J. L., Lopes, F., Courtillot, V., and Gibert, D. (2019). On Forcings of Length of Day Changes: From 9-day to 18.6-year Oscillations. *Phys. Earth Planet. Interiors* 292, 1–11. doi:10.1016/j.pepi.2019.04.006

Le Mouël, J. L., Lopes, F., and Courtillot, V. (2021b). Sea-Level Change at the Brest (France) Tide Gauge and the Markowitz Component of Earth's Rotation. *J. Coast. Res* 37 (4), 683–690. doi:10.2112/JCOASTRES-D-20-00110.1

Leandro, C. E., and Alvarado, G. E. (1988). Influencia de las mareas lunisolares sobre el comportamiento del volcán Arenal, Costa Rica. *Bol. Obs. Vulcanol. Arenal* 1 (2), 44–56.

Lopes, F., Le Mouël, J. L., Courtillot, V., and Gibert, D. (2021). On the Shoulders of Laplace. *Phys. Earth Planet. Interiors* 316, 106693. doi:10.1016/j.pepi.2021.106693

López, D. L., Bundschuh, J., Soto, G. J., Fernández, J. F., and Alvarado, G. E. (2006). Chemical Evolution of Thermal Springs at Arenal Volcano, Costa Rica: Effect of Volcanic Activity, Precipitation, Seismic Activity, and Earth Tides. *J. Volcanol. Geotherm. Res.* 157 (1-3), 166–181. doi:10.1016/j.jvolgeores.2006.03.049

Martin, D. P., and Rose, W. I, Jr (1981). Behavioral Patterns of Fuego Volcano, Guatemala. *J. Volcanol. Geotherm. Res.* 10 (1-3), 67–81.

Mason, B. G., Pyle, D. M., Dade, W. B., and Jupp, T. (2004). Seasonality of Volcanic Eruptions. *J. Geophys. Res. Solid Earth* 109 (B4), B04206. doi:10.1029/2002jb002293

Mauk, F. J., and Johnston, M. J. S. (1973). On the Triggering of Volcanic Eruptions by Earth Tides. *J. Geophys. Res.* 78 (17), 3356–3362. doi:10.1029/jb078i017p03356

Mauk, F. J., and Kienle, J. (1973). Microearthquakes at St. Augustine Volcano, Alaska, Triggered by Earth Tides. *Science* 182 (4110), 386–389. doi:10.1126/science.182.4110.386

McMillan, T. C., Rau, G. C., Timms, W. A., and Andersen, M. S. (2019). Utilizing the Impact of Earth and Atmospheric Tides on Groundwater Systems: A Review Reveals the Future Potential. *Rev. Geophys.* 57 (2), 281–315. doi:10.1029/2018rg000630

McNutt, S. R., and Beavan, R. J. (1987). Eruptions of Pavlof Volcano and Their Possible Modulation by Ocean Load and Tectonic Stresses. *J. Geophys. Res.* 92 (B11), 11509–11523. doi:10.1029/jb092ib11p11509

McNutt, S. R., and Beavan, R. J. (1984). Patterns of Earthquakes and the Effect of Solid Earth and Ocean Load Tides at Mount St. Helens Prior to the May 18, 1980, Eruption. *J. Geophys. Res.* 89 (B5), 3075–3086. doi:10.1029/jb089ib05p03075

McNutt, S. R., and Beavan, R. J. (1981). Volcanic Earthquakes at Pavlof Volcano Correlated with the Solid Earth Tide. *Nature* 294 (5842), 615–618. doi:10.1038/294615a0

McNutt, S. R. (1999). "Eruptions of Pavlof Volcano, Alaska, and Their Possible Modulation by Ocean Load and Tectonic Stresses: Re-evaluation of the Hypothesis Based on New Data from 1984-1998," in *Seismicity Patterns, Their Statistical Significance and Physical Meaning* (Basel: Birkhäuser), 701–712. doi:10.1007/978-3-0348-8677-2_23

McNutt, S. R. (1996). Seismic Monitoring and Eruption Forecasting of Volcanoes: a Review of the State-Of-The-Art and Case Histories. *Monit. Mitig. volcano hazards*, 99–146. doi:10.1007/978-3-642-80087-0_3

Miguelsanz, L., González, P. J., Tiampo, K. F., and Fernández, J. (2021). Tidal Influence on Seismic Activity during the 2011–2013 El Hierro Volcanic Unrest. *Tectonics* 40 (2), e2020TC006201. doi:10.1029/2020tc006201

Nakiboglu, S. M., and Lambeck, K. (1980). Deglaciation Effects on the Rotation of the Earth. *Geophys. J. Int.* 62 (1), 49–58. doi:10.1111/j.1365-246x.1980.tb04843.x

Neuberg, J. (2000). External Modulation of Volcanic Activity. *Geophys. J. Int.* 142 (1), 232–240. doi:10.1046/j.1365-246x.2000.00161.x

Neves, M. C., Cabral, J., Luttrell, K., Figueiredo, P., Rockwell, T., and Sandwell, D. (2015). The Effect of Sea Level Changes on Fault Reactivation Potential in Portugal. *Tectonophysics* 658, 206–220. doi:10.1016/j.tecto.2015.07.023

Newhall, C. G., Costa, F., Ratdomopurbo, A., Venezky, D. Y., Widiwijayanti, C., Win, N. T. Z., et al. (2017). WOVOdat–An Online, Growing Library of Worldwide Volcanic Unrest. *J. Volcanol. Geotherm. Res.* 345, 184–199. doi:10.1016/j.jvolgeores.2017.08.003

C. G. Newhall and R. Punongbayan (Editors) (1996). *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines* (Quezon City: Philippine Institute of Volcanology and Seismology), 1126.

Newhall, C. G., and Self, S. (1982). The Volcanic Explosivity Index (VEI) an Estimate of Explosive Magnitude for Historical Volcanism. *J. Geophys. Res.* 87 (C2), 1231–1238. doi:10.1029/jc087ic02p01231

Pagli, C., and Sigmundsson, F. (2008). Will Present Day Glacier Retreat Increase Volcanic Activity? Stress Induced by Recent Glacier Retreat and its Effect on Magmatism at the Vatnajökull Ice Cap, Iceland. *Geophys. Res. Lett.* 35 (9), L09304. doi:10.1029/2008gl033510

Patrick, M., Swanson, D., and Orr, T. (2019). A Review of Controls on Lava Lake Level: Insights from Halema 'uma 'u Crater, Kīlauea Volcano. *Bull. Volcanol.* 81 (3), 13. doi:10.1007/s00445-019-1268-y

Petrosino, S., Cusano, P., and Madonia, P. (2018). Tidal and Hydrological Periodicities of Seismicity Reveal New Risk Scenarios at Campi Flegrei Caldera. *Sci. Rep.* 8 (1), 13808–13812. doi:10.1038/s41598-018-31760-4

Petrosino, S., and Dumont, S. (2022). Tidal Modulation of Hydrothermal Tremor: Examples from Ischia and Campi Flegrei Volcanoes. *Front. Earth Sci.* 9, 775269. doi:10.3389/feart.2021.775269

Petrosino, S., Ricco, C., De Lauro, E., Aquino, I., and Falanga, M. (2020). Time Evolution of Medium and Long-Period Ground Tilting at Campi Flegrei Caldera. *Adv. Geosci.* 52, 9–17. doi:10.5194/adgeo-52-9-2020

Ricco, C., Petrosino, S., Aquino, I., Del Gaudio, C., and Falanga, M. (2019). Some Investigations on a Possible Relationship between Ground Deformation and Seismic Activity at Campi Flegrei and Ischia Volcanic Areas (Southern Italy). *Geosciences* 9 (5), 222. doi:10.3390/geosciences9050222

Roult, G., Peltier, A., Taisne, B., Staudacher, T., Ferrazzini, V., and Di Muro, A. (2012). A new comprehensive classification of the Piton de la Fournaise activity spanning the 1985-2010 period. Search and analysis of short-term precursors from a broad-band seismological station. *J. Volcanol. Geotherm. Res.* 241-242, 78–104. doi:10.1016/j.jvolgeores.2012.06.012

Rydelek, P. A., Davis, P. M., and Koyanagi, R. Y. (1988). Tidal Triggering of Earthquake Swarms at Kilauea Volcano, Hawaii. *J. Geophys. Res.* 93 (B5), 4401–4411. doi:10.1029/jb093ib05p04401

Satow, C., Gudmundsson, A., Gertisser, R., Ramsey, C. B., Bazargan, M., Pyle, D. M., et al. (2021). Eruptive Activity of the Santorini Volcano Controlled by Sea-Level Rise and Fall. *Nat. Geosci.* 14, 586–592. doi:10.1038/s41561-021-00783-4

Scholz, C. H., Tan, Y. J., and Albino, F. (2019). The Mechanism of Tidal Triggering of Earthquakes at Mid-Ocean Ridges. *Nat. Commun.* 10 (1), 1-7.

Seropian, G., Kennedy, B. M., Walter, T. R., Ichihara, M., and Jolly, A. D. (2021). A Review Framework of How Earthquakes Trigger Volcanic Eruptions. *Nat. Commun.* 12 (1), 1004–1013. doi:10.1038/s41467-021-21166-8

Shimozuru, D. (1987). Tidal Effects on Hawaiian Volcanism. *Volcanism Hawaii* 2, 1337–1343.

Siebert, L., Cottrell, E., Venzke, E., and Andrews, B. (2015). Earth's Volcanoes and Their Eruptions: an Overview. *Encycl. volcanoes*, 239–255. doi:10.1016/b978-0-12-385938-9.00012-2

Sigmundsson, F., Hooper, A., Hreinsdóttir, S., Vogfjörd, K. S., Ófeigsson, B. G., Heimisson, E. R., et al. (2015). Segmented Lateral Dyke Growth in a Rifting Event at Bárðarbunga Volcanic System, Iceland. *Nature* 517 (7533), 191–195. doi:10.1038/nature14111

Sottili, G., Lambert, S., and Palladino, D. M. (2021). Tides and Volcanoes: A Historical Perspective. *Front. Earth Sci.* 9, 777548. doi:10.3389/feart.2021.777548

Sottili, G., and Palladino, D. M. (2012). Tidal Modulation of Eruptive Activity at Open-Vent Volcanoes: Evidence from Stromboli, Italy. *Terra nova.* 24 (3), 233–237. doi:10.1111/j.1365-3121.2012.01059.x

Sparks, R. S. J. (1981). Triggering of Volcanic Eruptions by Earth Tides. *Nature* 290 (5806), 448.

Thomas, A. M., Nadeau, R. M., and Bürgmann, R. (2009). Tremor-tide Correlations and Near-Lithostatic Pore Pressure on the Deep San Andreas Fault. *Nature* 462 (7276), 1048–1051. doi:10.1038/nature08654

Tolstoy, M. (2015). Mid-ocean Ridge Eruptions as a Climate Valve. *Geophys. Res. Lett.* 42 (5), 1346–1351. doi:10.1002/2014gl063015

Watt, S. F. L., Pyle, D. M., and Mather, T. A. (2013). The Volcanic Response to Deglaciation: Evidence from Glaciated Arcs and a Reassessment of Global Eruption Records. *Earth-Science Rev.* 122, 77–102. doi:10.1016/j.earscirev.2013.03.007

Williams-Jones, G., Stix, J., Heiligmann, M., Barquero, J., Fernandez, E., and Gonzalez, E. D. (2001). A Model of Degassing and Seismicity at Arenal Volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* 108 (1-4), 121–139. doi:10.1016/s0377-0273(00)00281-x

Yakiwara, H., Hirano, S., Miyamachi, H., Takayama, T., Yamazaki, T., Tameguri, T., et al. (2013). Semi-Diurnal Tidal Periodicity Observed by an Ocean Bottom Seismometer Deployed at a Location Very Close to Seafloor Fumaroles in Wakamiko Caldera, Northeast of Sakurajima Volcano. *Bull. Volcanol. Soc. Jpn.* 58 (1), 269–279. doi:10.18940/kazan.58.1_269

Zaccagnino, D., Vespe, F., and Doglioni, C. (2020). Tidal Modulation of Plate Motions. *Earth-Science Rev.* 205, 103179. doi:10.1016/j.earscirev.2020.103179