Is There an Influence of the Pole Tide on Volcanism? Insights From Mount Etna Recent Activity

S. Lambert, G. Sottili

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2019GL085525

Is There an Influence of the Pole Tide on Volcanism? Insights From Mount Etna Recent Activity

S. Lambert[1] and G. Sottili[2]

[1]SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, Paris, France, [2]Dipartimento di Scienze della Terra, Sapienza-Università di Roma, Rome, Italy

Key Points:
- Seismicity and eruption timing and magnitudes at Mount Etna show interannual variations in phase with the solid Earth pole tide
- Earth's Chandler and annual wobbles may alter the state of stress of the Earth's crust at interannual to decadal timescales

Supporting Information:
- Supporting Information S1

Correspondence to:
S. Lambert,
sebastien.lambert@obspm.fr

Citation:
Lambert, S., & Sottili, G. (2019). Is there an influence of the pole tide on volcanism? Insights from Mount Etna recent activity. *Geophysical Research Letters*, *46*, 13,730–13,736. https://doi.org/10.1029/2019GL085525

Received 23 SEP 2019
Accepted 20 NOV 2019
Accepted article online 25 NOV 2019
Published online 3 DEC 2019

Abstract We investigate a possible link between polar motion and (i) seismic energy release and (ii) timing and intensity of eruptions at Mount Etna (Italy) for which a dense observational database is available. Our study suggests that the seismicity around Mount Etna increases during the largest excursions of the Earth rotation pole, which result from the constructive interference of the climate-driven seasonal and Chandler wobbles. To a lesser extent, a similar link is detected between the pole tide and the erupted volume of magma. We infer that, by creating periodic changes in the state of stress in the crust through a variable centrifugal force and a periodic vertical displacement (pole tide), variations in polar motion influence eruption timing and magnitude and the rate of seismic energy release from volcanoes. This study provides new evidences on the sensitivity of volcanoes to external forcing.

Plain Language Summary The Earth surface is continuously deformed by a wide range of phenomena including lunisolar tides and centrifugal forces due to changes in the Earth's rotation rate and in the direction of its rotation axis. The latter class of deformations is typically of a centimeter on interannual timescales. On another side, some volcanoes appear to be sensitive to small perturbations of the crustal stress. We detected similar variability in the centrifugal forces arising from the Earth's rotation axis direction variability and Mount Etna seismicity and erupted magma volume. This suggests that the variation of the Earth's rotation axis direction plays a significant role as modulator of the activity of Mount Etna.

1. Introduction

Though the Earth is mainly deformed by lunisolar tides (typically 30 cm/day), centrifugal forces arising from fluctuations in length-of-day (LOD) and polar motion also contribute at the level of a centimeter (cm) over seasonal to interannual timescales, the contribution from the latter being generally referred to as "solid Earth pole tide" (e.g., Lambeck, 1980). At seasonal and interannual timescales, polar motion is mainly composed of two retrograde oscillations at annual and 433-day periods with a beating period of 6.4 years. The latter, known as the Chandler wobble, results from the continuous climate-driven excitation of the free rotational mode associated with the Earth's ellipticity (e.g., Gross, 2000). Vertical displacements arising from polar motion are of the order of 1 cm at a latitude of 45°. Fluctuations in LOD, as the consequence of external tidal forcing and changes in the surface fluid and fluid core angular momentum (Hide et al., 2000; Hide & Dickey, 1991) are of few milliseconds at seasonal to multidecadal timescales, corresponding to a vertical displacement of roughly a millimeter at a latitude of 45°. Therefore, the solid Earth pole tide dominates the "LOD tide" by a factor of 10 (see Figures S1 and S2 in the supporting information).

In a variety of volcanically active regions worldwide, volcanic systems evolving toward a critical state have been found to be susceptible to small perturbations of the crustal stress state. Stress changes modulated by the LOD centrifugal forces—and estimated of the order of ~400 kPa/year (Sottili et al., 2015)—have been reported to produce crustal deformations on multiyear scale (Wang et al., 2000). They appear particularly significant in the different Earth's discontinuities as at lithospheric plate boundaries (Milyukov et al., 2013), lithosphere-asthenosphere boundary (Doglioni et al., 2011), and in crustal rocks surrounding magma reservoirs, thus affecting the eruptive behavior of volcanoes (Sottili et al., 2015). Active volcanoes are sensitive to other periodic crustal stress changes occurring over different timescales (see Table S2), as also reported for volcanoes along the "Ring of Fire" (Rymer & Brown, 1984; Kasahara et al., 2001; Palladino & Sottili, 2014); Stromboli, Italy (Johnston & Mauk, 1972; Sottili & Palladino, 2012); Kilauea, Hawaii

(Brown, 1925; Dzurisin, 1980); Mayon, Philippines (Jentzsch et al., 2001); Ruapehu, New Zealand (Girona et al., 2018); and Mount Etna (Patanè et al., 1994; Sottili et al., 2007). The centrifugal forces associated with pole tide are larger than those associated with LOD changes by a factor of 10. Nevertheless, although pole tide has been found to affect significantly crustal stress changes, for example, by modulating slow slip events at Circum-Pacific Subduction Zone (Zheng-Kang, 2005), their effects on active volcanoes has not yet been investigated.

Here we investigate a possible link between polar motion variations and seismicity and eruptive behavior at Mount Etna, whose latitude is 37°45′N. Specifically, we investigate whether the release of seismic energy in the vicinity of Mount Etna over the last 20 years, and in the volume of erupted magma since 1900, share common features with the vertical displacement arising from varying polar motion.

2. Data

2.1. Polar Motion

The Earth's rotation pole with respect to the crust is reckoned by two coordinates, m_1 and m_2, measured along the x (Greenwich meridian) and y (90° east) axes of the terrestrial reference frame, respectively. At a site of longitude λ and colatitude ϕ, the centrifugal force associated with this wobble produces a vertical displacement of (Petit & Luzum, 2010)

$$H = \frac{\Omega^2 a^2 h}{g} \sin\phi\cos\phi(m_1\cos\lambda + m_2\sin\lambda)$$

where Ω is the mean Earth's rotation rate, a is the mean Earth's radius, g is the mean gravity acceleration at the Earth's surface, and $h \sim 0.6$ is the Love number expressing the deformation of the Earth. As the pole wobble, H is modulated in about 6.4 years and the amplitude of the modulation is proportional to the pole radius

$$PR = \sqrt{m_1^2 + m_2^2}$$

where m_1 and m_2 are, here, detrended.

Polar motion has been recorded since 1846 by means of optical measurements, completed since the 1960s by space and geodetic techniques (very long baseline interferometry, laser ranging to artificial satellites, global navigation satellite system, and Doppler orbitography by radio positioning integrated on satellite). The accuracy of the data has drastically improved from several tens of milliarc second (mas; 1 mas is equivalent to 30 cm at the surface of the Earth) during the optical era to less than 0.1 mas after the 1990s. The data sets used in this study are the 14C01 (sampled at 0.05-yr) and daily 14C04 series (Bizouard et al., 2018) starting in 1846 and 1962, respectively. They are made available by the International Earth Rotation and Reference System Service Earth Orientation Center (Paris Observatory; http://iers.obspm.fr/eop-pc) and provide coordinates of observed rotation pole with respect to the conventional pole of the international terrestrial reference frame (Altamimi et al., 2016).

2.2. Seismicity

The Mount Etna seismicity displays the typical features of volcanically active regions with frequent earthquakes of moderate to low magnitude and shallow hypocenters, often shallower than 3 km (Gresta & Patanè, 1987). Previous works (e.g., Alparone et al., 2015) showed that the Mount Etna seismicity is related to several seismogenetic volumes, each characterized by different seismic rates and focal depths, with the volcano edifice eastern sector seismically very active. Patterns of Mount Etna seismogenetic faults and eruptive fissures show an apparent structural continuity as the result of complex interaction between regional tectonic stresses, gravity forces acting on the volcanic edifice and magma-induced rifting (Borgia et al., 1992; McGuire et al., 1996; Rasà et al., 1996). Interestingly, the historical seismicity at Mount Etna over the last two centuries is not uniformly distributed through time, with important seismic crises often accompanying major flank eruptions, as in 1883, 1886, 1908, 1984, and 1986, but sometimes occurring as temporally separated from eruptive events (Azzaro, 2004). Only over the last few decades the instrumental networks monitoring the seismicity at Mount Etna—mostly focused at determining the geophysical signals associated to magma upraise toward the surface—provides suitable magnitude thresholds and hypocenter

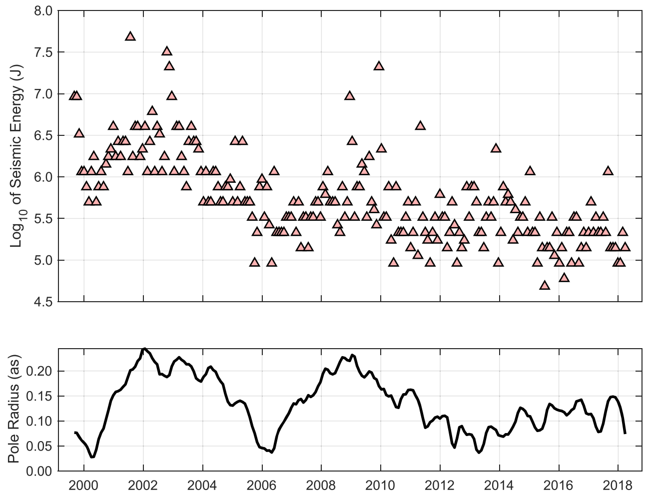

Figure 1. (top) Log_{10} of the seismic energy release (in J) versus time. Each triangle represents the median value in a bin of 1 month. (bottom) Pole radius in arcsecond (as) versus time.

locations for analyzing, in detail, the Etnean seismicity. In this light, we focused on seismic events recorded at Mount Etna since 1999 by the INGV—Istituto Nazionale di Geofisica e Vulcanologia (Gruppo Analisi Dati Sismici, 2018).

The data set consists of 11,263 events located within 43 km from the volcano summit area (Lat. 37°45′N Long. 15°00′E) with a median distance of 12 km. The local magnitude ML range from 0 to 4.8 with a median value of 1.5. The distribution is asymmetric with a longer tail on the side of larger magnitudes (see Figure S3). The hypocenter depth ranges between the surface down to 33.9 km. The distribution is strongly asymmetric with most of the recorded earthquakes occurring between 2.4 km (25th percentile) and 8.1 km (75th percentile) with a median value of 4.7 km.

Following Alparone et al. (2015), we computed the seismic energy release at Mount Etna using the (Richter, 1958) relationship

$$\log_{10}E = 9.9 + 1.9\,ML - 0.024\,ML^2$$

where ML is the local magnitude and the unit of E is 10^{-7} J.

2.3. Eruptions

To detect possible correlations between polar motion changes and volcanism, we considered the available erupted magma volume data set that includes both effusive and explosive activity of Mount Etna since 1900 (Andronico & Lodato, 2005; Allard et al., 2006; Behncke et al., 2014, 2016; Corsaro et al., 2017; Table S1); the chosen eruptive period, widely documented in both scientific literature and historical documents, should avoid reporting bias in the record. In historical times, Mount Etna eruptions consisted in sporadic explosive episodes at summit craters, frequent flank eruptions and, more rarely, eccentric eruptions lasting from a few hours to several months with erupted volumes up to 250×10^6 m^3 during single events. Estimations of magma volumes during effusive phases by lava flow fields digital mapping are affected by errors lower than 10% (Andronico & Lodato, 2005); the uncertainties associated to effusive volumes obtained by using satellite remote sensing range within ±20% (Ganci et al., 2018). Estimations of volumes of pyroclastic deposits are based on combined field observations, eruption column heights, and fallout duration with uncertainties within ~15% (e.g., Corsaro et al., 2017).

Previous works (Mulargia et al., 1985; Wadge & Guest, 1981) demonstrated that since 1600, the intensity of Mount Etna flank eruptions (i.e., the mass eruption rate) did not change significantly over the last four centuries, with eruptions occurrences randomly distributed with time as in a homogeneous Poisson process. Other authors suggested that the timing and intensity of eruptions occur at random and change over time as in an inhomogeneous Poisson process (Salvi et al., 2006). Through a simple time-predictable model, and by assuming a constant magma supply rate, it has been proposed that eruptions occur when the amount of stored magma reaches a critical value (Hill et al., 1998). Under these conditions, when the Mount Etna plumbing system is close to a critical state, the effects of decompression induced by external actions, as tidal forces (Sottili et al., 2007) and earthquakes (Bozzano et al., 2013) seem to affect the timing of eruptions at Mount Etna on short (days to hours) timescales. In our analysis, we considered the starting date and the magnitude of eruptions defined here as the logarithm of the erupted mass (in kg) of magma (e.g., Pyle, 2000). In light of the typical recharge times of Mount Etna feeder system (i.e., from a few months to years; see Andronico & Lodato, 2005; Corsaro et al., 2017), we considered the occurrence of eruptions separated by repose time shorter than 6 months as single eruptive events.

3. Results

3.1. Rates of Seismic Energy Release Versus Pole Radius

We averaged down both pole radius (PR) data, as derived from the 14C04 series, and seismic energy series over nonoverlapping intervals of 1 month, obtaining thus two consistent, evenly spaced time series with no missing data of length 227 months. Both series are shown in Figure 1. Their visual inspection reveals

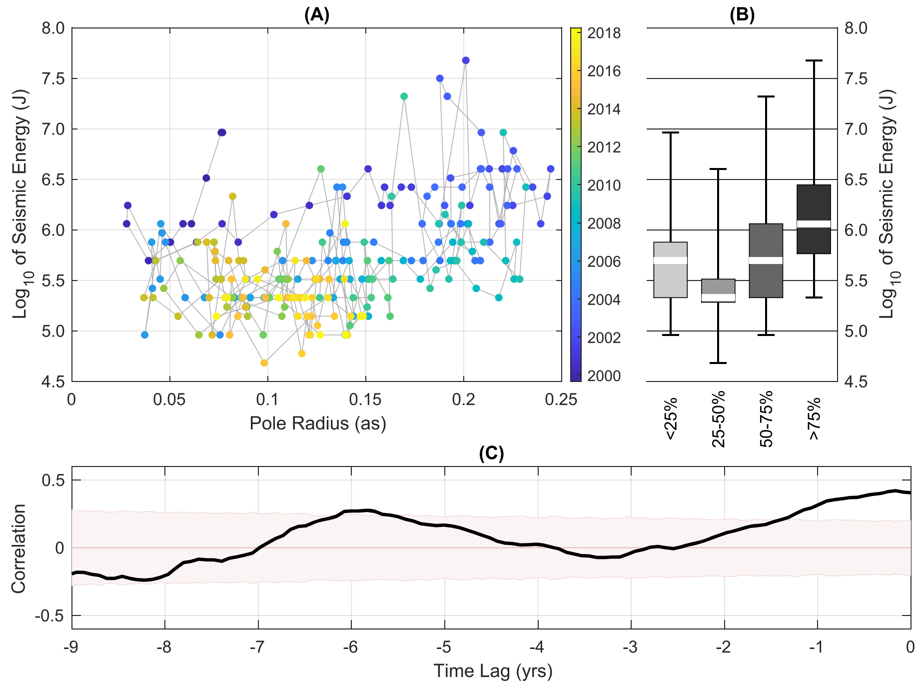

Figure 2. (a) Pole radius versus the $\log_{10}$ of the seismic energy release. (b) Boxplots of seismic energy values corresponding to four classes of pole radius. The bottom and top of the boxes correspond to first and third quartiles, respectively. The bottom and top whiskers represent the minimum and maximum values, respectively. The white, horizontal line is the median. (c) Correlation coefficient between PR and seismic energy release as a function of the time lag. The lag is reckoned as negative when PR variation precedes the seismic event. The pink band represents the 99% confidence interval (see text for details).

that they show common maxima around 2002 and 2009. A third expected maximum around 2015 in PR does not show up due to a rapidly decreasing amplitude of the Chandler wobble after 2010, letting the pole being driven by the annual wobble. The visual inspection of Figure 1 also reveals a long-term trend in seismic energy that could be related to multidecadal fluctuations of the seismicity associated with important seismic crises often accompanying major flank eruptions, as in 1883, 1886, 1908, 1984, and 1986 (e.g., Azzaro, 2004).

Figure 2a displays PR values versus the corresponding seismic energy release (gray triangles). At a first glance, the relationship between both quantities is not linear, except if one ignores low-PR data for which one could expect that PR influence be hidden by other stronger local sources of forcing. Nevertheless, we decided to keep the entire data and to use the rank correlation (Spearman's ρ coefficient) to assess a monotonic relation between the seismic energy and PR. Thus, we do not assume any linear relationship between the two quantities. We found $\rho = 0.41$ [0.25,0.54] where the brackets give the 99% confidence interval computed by adopting the null hypothesis that demeaned series are independent normally distributed data sets (e.g., Anderson, 1958). Both the confidence interval and the unusually small p value (1×10^{-10}) allow to consider the correlation as significantly different from zero. To enforce these evidences, we considered the four groups formed after the quartiles of the energy. We obtained the whiskers shown in Figure 2b suggesting similar evidences that the seismicity increases when the pole radius is larger.

We also computed the correlation coefficients between PR and the seismic energy series as a function of the time lag (reckoned as negative when PR variation precedes the event; see Figure 2c). The confidence interval on the correlation coefficient was estimated by a Monte Carlo method similarly to Sottili et al. (2015), evaluating the probability that correlations with $R^2 \geq 0.95$, $R^2 \geq 0.98$, and $R^2 \geq 0.99$ between PR and seismic energy may derive from random distributions of events onset times (null hypothesis) within the considered time window. This meant reshuffling the 227-month PR time series like a deck of cards

10.1029/2019GL085525

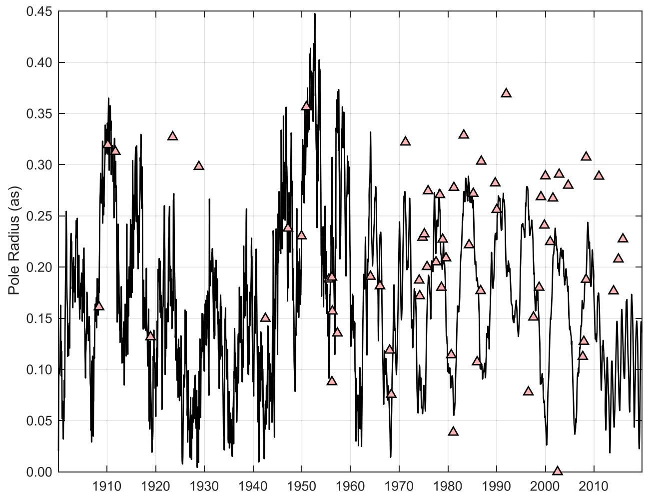

Figure 3. Volume of ejected magma (pink triangles) superimposed to the pole radius in arcsecond (solid, black line). Ejected magma volume was rescaled by a factor of ~0.28 so that its rms equals the rms of the pole radius and both quantities can be visually comparable.

and sampling for 1,000 times 227 random monthly seismic energy values to obtain a synthetic PDF distribution of 1,000 R^2 values (Figure S4) that shows a clear unimodal distribution and that the probability that $R^2 \geq 0.99$ derive from a random distribution of data can be rejected at the >99.5% confidence interval. Note that this evaluation guarantees that the results of our analysis on the correlation between PR and seismic energy are not affected by the random (in terms of time of occurrence) effects of a few, strong earthquakes. The maximum correlation is obtained for a lag of ~2 months (p value of 3×10^{-11}). For lags of a few years, the correlation drops down to nonstatistically significant values except for lags of about 6–7 years, consistently with the 6.4-year quasi-periodicity of PR due to the beating between the Chandler and seasonal wobbles.

Finally, we assessed the dependence of the correlation upon the selection radius around the crater, the length of the averaging window, the magnitude and depth (Figure S5). Results show that the positive and significant correlation claimed hereabove is robust when one changes the selection parameters. The filtering by bins of selection radius and depth suggests that some regions of Mount Etna volcanic system are preferably influenced by the pole tide: distance to the crater shorter than ~30 km and depths shorter than ~20 km. The correlation is the most significant for magnitudes between 1 and 2.5.

3.2. Size of Volcanic Eruptions Versus Pole Radius

We considered eruptions separated by repose times shorter than 6 months as a single eruptive event, as the typical recharge times preceding the main eruptive phases of Mount Etna have longer durations, that is, up to several years (Andronico & Lodato, 2005; Corsaro et al., 2017). This leads to 62 main eruptions that occurred since 1900 with a mean magma output rate in the order of 0.4–0.5 m^3/s. Effusive eruptions largely dominate, in terms of erupted volumes (~98%), the total amount of erupted magma (Table S1). We applied methods inspired by the previous section although the series of erupted magma volume are much sparser and nonevenly distributed (Figure 3). We tried several time lags between PR and the eruptive events. The optimal fitting of a linear relationship between the ejected magma volume and PR was achieved for a lag close to 0.5 year (see Figures S6 and 4a) with a slope of 2.8 [−0.6,6.2] and a Spearman's correlation coefficient of 0.27 [−0.06,0.55], that is, significant at 97% (p value of 0.03). The boxplots of Figure 4b also suggest the influence of PR for the largest eruptions.

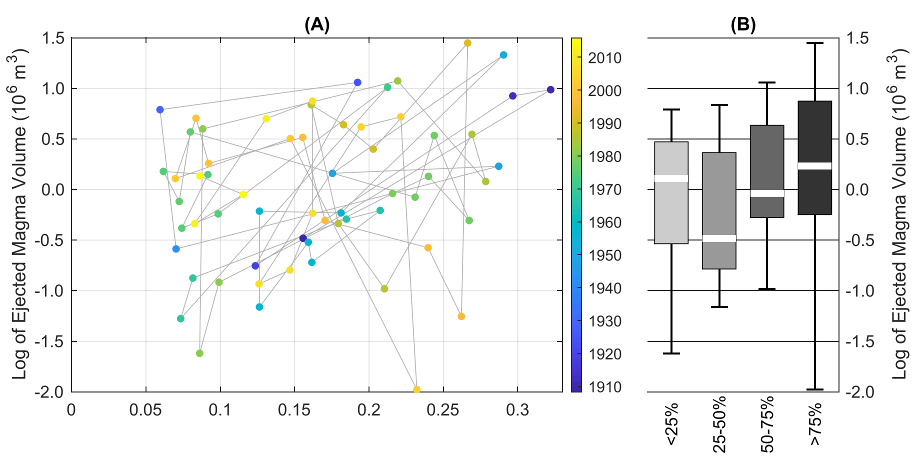

Figure 4. (a) Pole radius versus the $\log_{10}$ of the ejected magma volume. (b) Boxplots of ejected magma volume values corresponding to four classes of pole radius. The bottom and top of the boxes correspond to first and third quartiles, respectively. The bottom and top whiskers represent the minimum and maximum values, respectively. The white, horizontal line is the median.

4. Conclusions

Previous works (Bozzano et al., 2013; Sottili et al., 2007) brought evidences that, on hourly to daily timescales, the periodic decompression induced by tidal stresses on Mount Etna shallow plumbing system may act as a trigger mechanism for eruptive activity on condition that the eruptive system is already close to a critical state. At Mount Etna, this mechanism of tidal triggering of lava fountaining episodes is statistically more evident when the horizontal component of the quasi-diurnal tidal stresses acts in parallel with the ongoing eastern volcano flank instability (Sottili et al., 2007). At Mount St. Helens, the semidiurnal and quasi-diurnal tidal modulation of long-period seismic events interrupted ~2 months before the 18 May 1980 catastrophic flank collapse (McNutt & Beavan, 1984), thus revealing that the dramatic stress changes produced by the cryptodome intrusion overwhelmed the periodical pattern of seismicity due to tidal stress changes. Over longer timescales, our study, based on seismicity records since 1999 and erupted magma volume since 1900, suggests that the pole tide can excite the seismicity and, to a lesser extent, the eruptive activity at Mount Etna. Multiyear variations in eruption magnitude appear in phase with the beating between the Chandler wobble and the annual oscillation of polar motion that constitutes the main variability of the pole radius. We infer that, by creating periodic changes in the state of stress in the crust, variations in the polar motion can influence volcanism. Previous models (e.g., Sottili et al., 2015) demonstrated that horizontal stress induced by LOD changes, about 1 order of magnitude smaller than those related to PR changes, can produce significant effects on wall rocks of a magma chamber located in the shallow crust. We conclude also that differential stresses induced by PR changes can be relevant for the Mount Etna crustal plumbing system. The external modulation of eruptive and seismic activity at Mount Etna by pole tide widens the spectrum of known external forcing mechanisms influencing terrestrial volcanoes (see Table S2) and which investigation may help in understanding the present-day state of the volcanoes. At Mount Etna and other volcanoes affected by flank instability phenomena, future observations on time-varying sensitivities to external forcings (e.g., Earth's tides, pole tide, LOD) may help identify the transition of magmatic systems toward critical states (i.e., eruptions and/or major flank instability events approaching) possibly culminating in catastrophic failure and debris avalanches.

Acknowledgments
The data used in this study arearchived in relevant public repositories. The seismic data set is available through the Gruppo Analisi Dati Sismici, Catalogo dei terremoti della Sicilia Orientale-Calabria Meridionale (1999–2018), Istituto Nazionale Geofisica e Vulcanologia (INGV), Catania, at http://www.ct.ingv.it/ufs/analisti/catalogolist.php. The Earth's rotation series are available at the Paris Observatory IERS Earth Orientation Center at http://iers.obspm.fr/iers/eop/eopc01/eopc01.1846-now for the C01 data since 1846, and at http://iers.obspm.fr/iers/eop/eopc04/eopc04.62-now for the C04 data since 1962. It is a pleasure to acknowledge the Editor Rebecca Carey, Prof. Peter Varga and Johnathan Rougiers, and two anonymous referees for helping in improving the manuscript.

References

Allard, P., Behncke, B., D'Amico, S., Neri, M., & Gambino, S. (2006). Mount Etna 1993–2005: Anatomy of an evolving eruptive cycle. *Earth-Science Reviews*, *78*(1-2), 85–114. https://doi.org/10.1016/j.earscirev.2006.04.002

Alparone, S., Maiolino, V., Mostaccio, A., Scaltrito, A., Ursino, A., Barberi, G., et al. (2015). Instrumental seismic catalogue of Mount Etna earthquakes (Sicily, Italy): Ten years (2000–2010) of instrumental recordings. *Annals of Geophysics*, *58*, S0435. https://doi.org/10.4401/ag-6591

Altamimi, Z., Rebischung, P., Métivier, L., & Collilieux, X. (2016). ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions. *Journal of Geophysical Research: Solid Earth*, *121*(8), 6109–6131. https://doi.org/10.1002/2016JB013098

Anderson, T. (1958). *An introduction to multivariate statistical analysis* (3rd ed.p. 747). New York: Wiley.

Andronico, D., & Lodato, L. (2005). Effusive activity at Mount Etna volcano (Italy) during the 20th century: A contribution to volcanic hazard assessment. *Natural Hazards*, *36*(3), 407–443. https://doi.org/10.1007/s11069-005-1938-2

Azzaro, R. (2004). *Seismicity and active tectonics in the Etna region: Constraints for a seismotectonic model*, *Geophysical Monograph Series* (Vol. 143, pp. 205–220). Washington, DC: American Geophysical Union.

Behncke, B., Branca, S., Corsaro, R. A., De BDeeni, E., Miraglia, L., & Proietti, C. (2014). The 2011–2012 summit activity of Mount Etna: Birth, growth and products of the new SE crater. *Journal of Volcanology and Geothermal Research*, *270*, 10–21. https://doi.org/10.1016/j.jvolgeores.2013.11.012

Behncke, B., Fornaciai, A., Neri, M., Favalli, M., Ganci, G., & Mazzarini, F. (2016). Lidar surveys reveal eruptive volumes and rates at Etna, 2007–2010. *Geophysical Research Letters*, *43*, 4270–4278. https://doi.org/10.1002/2016GL068495

Bizouard, C., Lambert, S., Gattano, C., Becker, O., & Richard, J.-Y. (2018). The IERS EOP 14C04 solution for Earth orientation parameters consistent with ITRF 2014. *Journal of Geodesy*, *93*(5), 621–633. https://doi.org/10.1007/s00190-018-1186-3

Borgia, A., Ferrari, L., & Pasquare, G. (1992). Importance of gravitational spreading in the tectonic evolution of Mount Etna. *Nature*, *357*(6375), 231–235. https://doi.org/10.1038/357231a0

Bozzano, F., Gaeta, M., Lenti, L., Martino, S., Paciello, A., Palladino, D. M., & Sottili, G. (2013). Modeling the effects of eruptive and seismic activities on flank instability at Mount Etna, Italy. *Journal of Geophysical Research: Solid Earth*, *118*, 5252–5273. https://doi.org/10.1002/jgrb.50377

Brown, E. W. (1925). Tidal oscillations in Halemaumau, the lava pit of Kilauea. *American Journal of Science*, *9*, 95–112.

Corsaro, R. A., Andronico, D., Behncke, B., Branca, S., Caltabiano, T., Ciancitto, F., et al. (2017). Monitoring the December 2015 summit eruptions of Mount Etna (Italy): Implications on eruptive dynamics. *Journal of Volcanology and Geothermal Research*, *341*, 53–69. https://doi.org/10.1016/j.jvolgeores.2017.04.018

Doglioni, C., Ismail-Zadeh, A., Panza, G., & Riguzzi, F. (2011). Lithosphere-asthenosphere viscosity contrast and decoupling. *Physics of the Earth and Planetary Interiors*, *189*(1-2), 1–8. https://doi.org/10.1016/j.pepi.2011.09.006

Dzurisin, D. (1980). Influence of fortnightly Earth tides at Kilauea Volcano, Hawaii. *Geophysical Research Letters*, *7*(11), 925–928. https://doi.org/10.1029/GL007i011p00925

Ganci, G., Cappello, A., Bilotta, G., Hérault, A., Zago, V., & Del Negro, C. (2018). Mapping volcanic deposits of the 2011–2015 Etna eruptive events using satellite remote sensing. *Frontiers in Earth Science*, *6*, 83. https://doi.org/10.3389/feart.2018.00083

Girona, T., Huber, C., & Caudron, C. (2018). Sensitivity to lunar cycles prior to the 2007 eruption of Ruapehu volcano. *Scientific Reports*, *8*(1), 1–9. https://doi.org/10.1038/s41598-018-19307-z

Gresta, S., & Patanè, G. (1987). Review of seismological studies at Mount Etna. *Pure and Applied Geophysics*, *125*(6), 951–970. https://doi.org/10.1007/BF00879362

Gross, R. S. (2000). The excitation of the Chandler wobble. *Geophysical Research Letters*, *27*(15), 2329–2332. https://doi.org/10.1029/2000GL011450

Gruppo Analisi Dati Sismici (2018) Catalogo dei terremoti della Sicilia Orientale-Calabria Meridionale (1999-2018) INGV, Catania. http://www.ct.ingv.it/ufs/analisti/catalogolist.php.

Hide, R., Boggs, D. H., & Dickey, J. O. (2000). Angular momentum fluctuations within the Earth's liquid core and torsional oscillations of the core–mantle system. *Geophysical Journal International*, *143*(3), 777–786. https://doi.org/10.1046/j.0956-540X.2000.01283.x

Hide, R., & Dickey, J. O. (1991). Earth's variable rotation. *Science*, *253*(5020), 629–637. https://doi.org/10.1126/science.253.5020.629

Hill, B., Connor, C., Jarzemba, M., La Femina, P., Navarro, M., & Strauch, W. (1998). 1995 eruptions of Cerro Negro volcano, Nicaragua, and risk assessment for future eruptions. *Bulletin Geological Society of America*, *110*(10), 1231–1241. https://doi.org/10.1130/0016-7606(1998)110<1231:EOCNVN>2.3.CO;2

Jentzsch, G., Haase, O., Kroner, C., & Winter, U. (2001). Mayon volcano, Philippines: Some insight into stress balance. *Journal of Volcanology and Geothermal Research*, *109*(1-3), 205–217. https://doi.org/10.1016/S0377-0273(00)00312-7

Johnston, M. J. S., & Mauk, F. J. (1972). Earth tides and the triggering of eruptions from Mt Stromboli, Italy. *Nature*, *239*(5370), 266–267. https://doi.org/10.1038/239266b0

Kasahara, J., Nakao, S., & Koketsu, K. (2001). Tidal influence on the 2000 Miyake-jima eruption and its implications for hydrothermal activity and volcanism. *Proceedings Japan Academy*, *77*(6), 98–103. https://doi.org/10.2183/pjab.77.98

Lambeck, K. (1980). *The Earth's variable rotation: Geophysical causes and consequences*. Cambridge: Cambridge University Press.

McGuire, W. J., Moss, J. L., Saunders, S. J., Stewart, I. S. (1996) Dyke-induced rifting and edifice instability at Mount Etna, in *Etna: Fifteen years on*, edited by P. J. Gravestock and W. J. McGuire, 20-24, Cheltenham, UK.

McNutt, S. R., & Beavan, R. J. (1984). Patterns of earthquakes and the effect of solid Earth and ocean load tides at Mount St. Helens prior to May 18, 1980 eruption. *Journal of Geophysical Research*, *89*(B5), 3075–3086. https://doi.org/10.1029/JB089iB05p03075

Milyukov, V., Mironov, A., Kravchuk, V., Amoruso, A., & Crescentini, L. (2013). Global deformations of the Eurasian plate and variations of the Earth rotation rate. *Journal of Geodynamics*, *67*, 97–105. https://doi.org/10.1016/j.jog.2012.05.009

Mulargia, F., Tinti, S., & Boschi, E. (1985). A statistical analysis of flank eruptions on Etna volcano. *Journal of Volcanology and Geothermal Research*, *23*(3-4), 263–272. https://doi.org/10.1016/0377-0273(85)90037-X

Palladino, D. M., & Sottili, G. (2014). Earth's spin and volcanic eruptions: Evidence for mutual cause-and-effect interactions? *Terra Nova*, *26*(1), 78–84. https://doi.org/10.1111/ter.12073

Patanè, G., Frasca, A., Agodi, A., & Imposa, S. (1994). Earth tides and Etnean volcanic eruptions: An attempt of correlation of the two phenomena during the 1983, 1985 and 1986 eruptions. *Physics of the Earth and Planetary Interiors*, *87*(1-2), 123–135. https://doi.org/10.1016/0031-9201(94)90026-4

Petit, G., & Luzum, B. (2010). *Conventions 2010. IERS technical note 36* (p. 179). Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie. ISBN: 3-89888-989-6.

Pyle, D. M. (2000). Sizes of volcanic eruptions. In H. Sigurdsson, et al. (Eds.), *Encyclopedia of volcanoes* (pp. 263–269). San Diego, CA: Academic Press.

Rasà, R., Azzaro, R., & Leonardi, O. (1996). Aseismic creep on faults and flank instability at Mount Etna volcano, Sicily. In W. C. McGuire, A. P. Jones, & J. Neuberg (Eds.), *Volcano Instability on the Earth and Other Planets*, *Special Publications* (Vol. 110, pp. 179–192). London: Geological Society of London.

Richter, C. F. (1958). *Elementary seismology*. San Francisco: Freeman.

Rymer, H., & Brown, G. C. (1984). Periodic gravity changes at Poàs volcano, Costa Rica. *Nature*, *311*(5983), 243–245. https://doi.org/10.1038/311243a0

Salvi, F., Scandone, R., & Palma, C. (2006). Statistical analysis of the historical activity of Mount Etna, aimed at the evaluation of volcanic hazard. *Journal of Volcanology and Geothermal Research*, *154*(3-4), 159–168. https://doi.org/10.1016/j.jvolgeores.2006.01.002

Sottili, G., Martino, S., Palladino, D. M., Paciello, A., & Bozzano, F. (2007). Effects of tidal stresses on volcanic activity at Mount Etna, Italy. *Geophysical Research Letters*, *34*, L01311. https://doi.org/10.1029/2006GL028190

Sottili, G., & Palladino, D. M. (2012). Tidal modulation of eruptive activity at open-vent volcanoes: Evidence from Stromboli, Italy. *Terra Nova*, *24*(3), 233–237. https://doi.org/10.1111/j.1365-3121.2012.01059.x

Sottili, G., Palladino, D. M., Cuffaro, M., & Doglioni, C. (2015). Earth's rotation variability triggers explosive eruptions in subduction zones. *Earth, Planets and Space*, *67*, 208. https://doi.org/10.1186/s40623-015-0375-z

Wadge, G., & Guest, J. E. (1981). Steady state magma discharge at Etna 1971–1981. *Nature*, *294*(5841), 548–550. https://doi.org/10.1038/294548a0

Wang, Q.-L., Chen, Y.-T., Cui, D.-X., Wang, W.-P., & Liang, W.-F. (2000). Decadal correlation between crustal deformation and variation in length of day of the Earth. *Earth, Planets and Space*, *52*(11), 989–992. https://doi.org/10.1186/BF03352318

Zheng-Kang, S. (2005). Pole-tide modulation of slow slip events at Circum-Pacific Subduction Zones. *Bulletin of the Seismological Society of America*, *95*, 2009–2015. https://doi.org/10.1785/0120050020