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The Co-Incidence of Earthquakes and Volcanoes: Assessing Global Volcanic Radiant Flux Responses to Earthquakes in the 21st Century

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Abstract

The temporal and spatial co-incidence of earthquakes and volcanoes has been documented for many years with recent reports suggesting that instances of earthquake-induced volcanic activity often occur following high magnitude seismic events. Using data extracted from the MODVOLC algorithm, this paper compares global volcanic radiant fluxes with global seismic energy to investigate temporal co-incidences between earthquakes and volcanic activity and to identify the thermal response of volcanoes to 14 large magnitude ($M_w \geq 8.0$) earthquakes that occurred between 2001 and 2011. Results indicate that, on the basis of statistical testing, 3 events were associated with a statistically significant increase in global volcanic radiant flux by more than half and, 2 events experienced a statistically significant decrease in global volcanic activity. In the remaining 9 cases, global volcanic activity remained unchanged. These findings indicate that (1) at a global scale, there are instances of a temporally co-incident relationship between global seismic energy and global volcanic radiant flux, (2) modified thermal activity following an earthquake is short-lived, often reflected in changes in the number of thermally active volcanoes and/or global volcanic radiant flux and, (3) under favourable conditions, volcanoes with long repose periods may be more susceptible to triggering.

Keywords: earthquake-volcano interactions, thermal anomalies, remote sensing

1 Introduction

There is mounting evidence of a temporal link between volcanic activity and large magnitude earthquakes (e.g. Linde and Sacks 1998; Hill et al. 2002; Marzocchi 2002; Manga and Brodsky 2006; Eggert and Walter 2009; Delle Donne et al. 2010; Avouris et al. 2017; Nishimura 2017; Sawi and Manga 2018). Linde and Sacks (1998), for example, showed that there were significantly more eruptions on days of large earthquakes than would be expected by chance. Whereas Marzocchi (2002) suggested that responses could be observed up to decades (0-5 years in 5/8 cases and 30-35 years in 2/4 cases) after an earthquake, Walter and Amelung (2007) noted significant increases in post-earthquake eruption rates up to 3 years following an event, and Sawi and Manga (2018) reported a 5-12% increase in the number of explosive eruptions 2 months to 2 years following large magnitude earthquakes. Similarly, while some volcanoes may show immediate signs of volcanic unrest following large magnitude earthquakes (reflected, for example, in changes in seismicity (Hill at al. 1995; Power et al. 2001; Prejean et al. 2004; West et al. 2005), degassing (Avouris et al. 2017), deformation (Pritchard et al. 2013) or fumarole activity (Walter et al. 2007)), others may only exhibit signs of earthquake-induced volcanic activity weeks to months following an earthquake (e.g. Manga and Brodsky 2006; Battaglia et al. 2012; Prejean and Haney 2014). The issue that arises, therefore, is establishing any association between these events and the timescales on which they act.

When considering the spatial influence of earthquakes on volcanoes, studies have again shown conflicting results with statistical evidence of earthquake-induced volcanic activity being present at a local (<200 km), regional (<1,000 km) and global scale (Alam et al. 2004; Gresta et al. 2005; Harris and Ripepe 2007; Walter 2007; Walter and Amelung 2007; Eggert and Walter 2009; Watt et al. 2009; Cannata et al. 2010; De la Cruz-Reyna et al. 2010; Delle Donne et al. 2010; Chao et al. 2013; Takada and Fukushima 2013; Nishimura 2017). For volcanoes located near the epicentre (<200 km) of $M_w \geq 7.5$ earthquakes, Nishimura (2017) indicated that the probability of volcanic eruptions increases by 50%, 0-5 years after an event. Whereas, Marzocchi et al. (2004) found that changes in stress following the passage of seismic waves can result in the re-activation and triggering of volcanoes up to 1,000 km from an earthquake's epicentre. At a global scale, comparisons of volcanic activity before and after an earthquake found that instances of unrest increased following an earthquake (Prejean et al. 2004; West et al. 2005; Watt et al. 2009; Cannata et al. 2010; Delle Donne et al. 2010; Chao et al. 2013). Following the 2004 $M_w 9.1$ Sumatra earthquake (26/12/2004), for example, instances of earthquake-induced volcanic unrest demonstrated the potential of a global relationship. One year after the event, Walter and Amelung (2007) found a four times increase in the average eruption rate (as compared to before). Similarly, West et al. (2005) observed an 11-minute swarm of triggered seismicity at Mount Wrangell, 11,000 km away. The majority of studies at a global scale, however, have been focused on individual volcanoes (e.g. West et al. 2005) or have been based on historical records (e.g. Linde and Sacks 1998; Manga and Brodsky 2006; Walter and Amelung 2007; Nishimura 2017) meaning that earthquake-volcano interactions at this scale are hard to quantify.

For volcanoes that have been triggered, responses may include new eruptive activity, new periods of unrest or changes in on-going activity (Hill et al. 2002; West et al. 2005; Eggert and Walter 2009; Ozawa and Fujita 2013; Pritchard et al. 2013; Avouris et al. 2017). In many cases, earthquake-induced volcanic activity most often results in subtle changes in behaviour, with few cases of explosive volcanic eruptions being recorded. It is not surprising, therefore, that varying responses (spatially, temporally, and in terms of the type of activity experienced) mean that earthquake-induced volcanic activity remains poorly understood.

This research examines volcanic radiant flux at a global scale to evaluate the potential of large magnitude earthquakes to modify volcanic activity. Large magnitude earthquakes, in particular, have been shown to modify the probability of volcanic unrest and, considering their tendency to be located in subduction zones with large rupture lengths, such high magnitude events are more likely to exhibit a global influence. Fortunately, the availability of infrared data measured via satellite remote sensing can act as a proxy for volcanic activity and has been used to monitor a range of explosive and effusive events including volcanic gas emissions, lava-flow-forming eruptions, variations in eruption intensity and the development of lava lakes (Harris and Stevenson 1997; Harris and Thornber 1999; Harris et al.

2000; Wright et al. 2002; Wright et al. 2015) as well as earthquake-induced thermal volcanic activity (Harris and Ripepe 2007; Delle Donne et al. 2010; Bonali et al. 2013; Pritchard et al. 2013).

2 Data and Methods

2.1 USGS Global Earthquake Catalog

The United States Geological Survey National Earthquake Information Centre (USGS NEIC) maintains an archive of all seismic events and is considered mostly complete for all $M_w \geq 4.5$ earthquakes occurring worldwide (USGS 2019). Data on the time, location, depth and magnitude of all earthquakes are recorded by the NEIC global network and contributing agencies and reported on the USGS Earthquake Catalog website.

2.2 MODVOLC: A Volcanic Hotspot Detection System

By virtue of their nature, volcanoes emit heat when they erupt and this can be detected remotely by sensors on-board many Earth-orbiting satellites. For those volcanoes displaying thermally anomalous activity, an automated detection system exists: MODVOLC (Wright et al. 2002; Wright et al. 2004; Wright 2016). MODVOLC detects and monitors the infrared radiation emitted by volcanoes, thereby providing a time series of thermal volcanic behaviour that extends back to 2000. Using data acquired from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, MODVOLC determines the presence of high temperature features within a 1 km pixel based on their spectral radiance in the middle (3.959 μm) and longwave (12.02 μm) infrared wavebands (Wright et al. 2002; Wright 2016). This data is made available on the MODVOLC Volcano Thermal Alert System and can be processed to determine the intensity of volcanic hotspots, providing a robust method to measure the global response of volcanoes to large magnitude earthquakes through time.

2.3 Methods

The MODVOLC database was queried to identify all volcanoes that exhibited thermal activity between 28 February 2000 and 31 December 2012. After considering only night-time observations (Flynn et al. 2002; Wright et al. 2015), thermal anomalies were detected at 99 volcanoes. For each high temperature pixel, the spectral radiance was converted to radiative power, E_f (MW), using the MIR Brightness-Temperature method (Kaufman et al. 1998):

$$E_f = 4.34\ x\ 10^{-19}\left(T_{4h}^{8} - T_{4b}^{8}\right)$$

where T_{4h}^{8} (in K) is the hotspot pixel temperature at 3.959 μm (MODIS channel 22, or 21 if temperature exceeds 335 K) converted from spectral radiance using Planck's blackbody radiation law and, T_{4b}^{8} (in K) is the surrounding ambient surface temperature where an independent estimate of background temperature for each volcano (averaged for each calendar month from the analysis of MOD11 and MYD11, 2000-2010) was obtained from the MODIS Land Surface Temperature product (Wright et al. 2015). For each volcano, E_f for all pixels per calendar day were summed to provide a daily volcanic radiant flux (Total). The daily volcanic radiant flux for each volcano was then summed to determine the Global Volcanic Radiant Flux for each calendar day for all thermally active volcanoes, G_{VRF}.

To assess the influence of large magnitude subduction zone earthquakes on global volcanic activity, the MODVOLC-derived G_{VRF} (Global Volcanic Radiant Flux for each calendar day for all thermally active volcanoes) inventory was compared with all $M_w \geq 8.0$ earthquakes that occurred between 28 February 2001 and 31 December 2011. For each earthquake, change in G_{VRF} was considered over a 731-day window where the percentage change in summed G_{VRF} up to 365 days following an event was compared to the 365 days preceding the event, i.e. a time window analysis comparing each day up to 365 days before and after the day of the earthquake, to determine whether global volcanic flux remained unchanged, increased (i.e. positive response) or decreased (i.e. negative response). A 731-day window was chosen in order to reflect the time taken for changes within a magma chamber to manifest in an eruption or period of unrest (Nostro et al. 1998; Hill et al. 2002; Watt et al. 2009; Feuillet et al. 2011; Jay et al. 2013). For each earthquake analysed, G_{VRF} was compared to the inter-annual variability (v + 1σ, where v is the 12-year average and σ is the number of standard deviations above the average) to identify changes in global volcanic flux. To establish the significance of each earthquake-volcano co-incidence, a probability density function (P_x) was calculated which queried the maximum change in G_{VRF} for each event in comparison to a set of randomly generated change in G_{VRF} values. Given that a probability density function (P_x) determines the likelihood of a calculated value within a sample, in this study any value of $P_x \geq 0.005$ signifies a statistically significant change in G_{VRF}.

To assess whether earthquakes also influenced the number of thermally active volcanoes, the average number of thermally active volcanoes in the 365 days preceding, N_b, and following, N_a, each earthquake were examined. To evaluate the significance of any association between earthquakes and the number of active volcanoes, corresponding β-statistics, a statistical test previously applied in seismology (e.g. Matthews and Reasenberg 1988; Reasenberg and Simpson 1992; Hough 2005), were calculated:

$$\beta = N_a - N_e/\sqrt{v}$$

where N_e represents the expected number of active volcanoes based on N_b and v is the variance of N_e. As the β-statistic represents the number of standard deviations from which the rate of potential triggering differs from the expected background estimate (Hill and Prejean 2015), positive values indicate that the number of active volcanoes increased following an earthquake and negative values indicate a decrease. On this basis, large reported values demonstrate the significance of triggering and for this study an associated β-statistic > ±150 was used to indicate a significant change in the number of active volcanoes. In order to identify instances of temporally co-incident changes in global volcanic activity following earthquakes, both a statistically significant change in G_{VRF} ($P_x > 0.005$) and the numbering of thermally active volcanoes (β-statistic > ±150) had to be met.

3 Results: Global Volcanic Radiant Flux Responses to Large Magnitude ($M_w \geq 8.0$) Earthquakes

Of the 14 potential earthquake-volcano co-incidences identified (Figure 1), statistically significant increases in global volcanic activity ($P_x > 0.005$) were observed following 5 $M_w \geq 8.0$ events and statistically significant decreases in thermal activity were encountered following 4 events (Table 1). Examination of the change in G_{VRF} showed that following 3 earthquake events (M_w 8.4 Peru, 23/06/2001; M_w8.1 Macquarie Islands, 23/12/2004 and M_w9.1 Sumatra, 26/12/2004), global volcanic activity more than doubled, while 2 events (M_w8.0 Peru, 15/08/2007 and M_w8.4 Sumatra, 12/09/2007) resulted in a decrease in global volcanic activity by more than half. In 10 cases, the change in the number of active volcanoes (N_a/N_b) was at least ±10%, with a corresponding β-statistic (> ±150) indicating that following 6 events (M_w8.4 Peru, 23/06/2001; M_w8.1 Japan, 25/09/2003; M_w8.1 Macquarie Islands, 23/12/2004; M_w 9.1 Sumatra, 26/12/2004; M_w 8.1 Samoa Islands, 29/09/2009 and M_w 8.8 Chile, 27/02/2010) the change in the number of erupting volcanoes was significant. However on the basis of the β-statistic and P_x, only 5 of these events (M_w8.4 Peru, 23/06/2001; M_w8.1 Japan, 25/09/2003; M_w8.1 Macquarie Islands, 23/12/2004; M_w9.1 Sumatra, 26/12/2004 and M_w8.8 Chile, 27/02/2010) may be temporally co-incident.

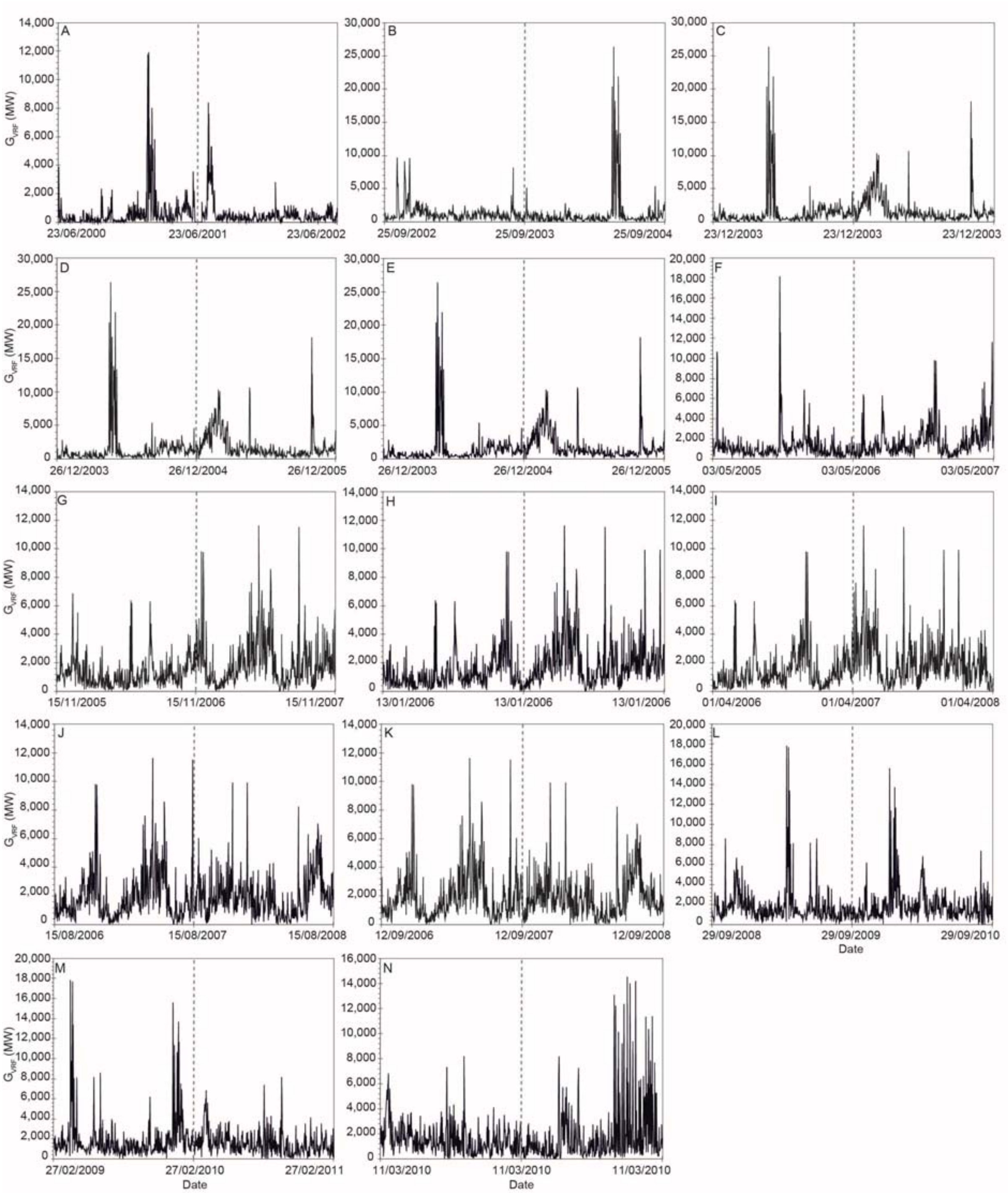

Figure 1 G_{VRF} (black line) ±365 days for each $M_w \geq 8.0$ earthquake (grey dashed line) identified in Table 1. A) M_w8.4 Peru, 23/06/2001 – Positive response, B) M_w8.1 Japan, 25/09/2003 – Negative response, C) M_w 8.1 Macquarie Islands, 23/12/2004 – Positive response, D) M_w 9.1 Sumatra, 26/12/2004 – Positive response, E) M_w8.6 Sumatra, 28/03/2005 – Unchanged, F) M_w8.0 Tonga, 03/05/2006 – Unchanged, G) M_w8.3 Kuril Islands, 15/11/2006 – Unchanged, H) M_w8.1 Kuril Islands, 13/01/2007 – Unchanged, I) M_w8.1 Solomon Islands, 01/04/2007 – Unchanged, J) M_w8.0 Peru, 15/08/2007 – Unchanged, K) M_w8.4 Sumatra, 12/09/2007 – Unchanged, L) M_w8.1 Samoa Islands,

29/09/2009 – Unchanged, M) M_w 8.8 Chile, 27/02/2010 – Negative response, N) M_w 9.1 Japan, 11/03/2011 – Unchanged.

Table 1 Global volcanic radiant flux responses to $M_w \geq 8.0$ earthquakes, 2001-2011. N_b *(Total)* and N_a *(Total)* reports the average (and, total) number of active volcanoes 365 days *preceding* and *following* an earthquake, respectively. *Change in the Number of Active Volcanoes (%)* and N_a/N_b indicate the change in the daily number of active volcanoes. *β-statistic* indicates the significance of any association between earthquakes and the number of active volcanoes. *Change in Radiant Flux (%)* indicates the largest daily percentage change in summed volcanic radiant flux up to 365 days following the earthquake as compared to the same number of days preceding the earthquake up to 365 days. $P_{(X)}$ reports the probability density function for the *Change in Radiant Flux*. *Lag (Days)* reports the number of days for the largest percentage change in radiant flux up to 365 days following the earthquake to occur. *Response* indicates if global volcanic flux remained unchanged, increased (i.e. positive) or decreased (i.e. negative). Rows highlighted in grey highlight positive and negative responses, which met all criteria to be classed as a temporally co-incident.

Earthquake Date	Earthquake Magnitude	Location	N_b (Total)	N_a (Total)	Change in Number of Active Volcanoes (%)	N_a/N_b	β-Statistic	Change in Radiant Flux (%)	P_X	Lag (Days)	Response
23/06/2001	8.4	Peru	2.89 (1057)	3.61 (1321)	24.98	1.25	158.11	104.38	0.0010	44	Positive
25/09/2003	8.1	Japan	6.07 (2220)	3.96 (1451)	-34.64	0.65	-343.31	-39.20	0.0043	216	Negative
23/12/2004	8.1	Macquarie Islands	4.57 (1672)	6.96 (2549)	52.45	1.52	460.44	141.87	0.0001	73	Positive
26/12/2004	9.1	Sumatra	4.60 (1685)	6.96 (2549)	51.28	1.51	454.00	140.40	0.0001	75	Positive
28/03/2005	8.6	Sumatra	5.70 (2087)	6.61 (2418)	15.86	1.16	137.06	26.86	0.0088	1	Unchanged
03/05/2006	8.0	Tonga	6.57 (2404)	7.33 (2683)	11.61	1.12	148.97	81.90	0.0027	81	Unchanged
15/11/2006	8.3	Kuril Islands	6.81 (2491)	7.15 (2617)	5.06	1.05	61.32	78.72	0.0031	286	Unchanged
13/01/2007	8.1	Kuril Islands	6.72 (2458)	7.16 (2621)	6.63	1.07	75.22	60.65	0.0052	363	Unchanged
01/04/2007	8.1	Solomon Islands	7.13 (2608)	6.71 (2456)	-5.83	0.94	-64.57	-30.54	0.0054	2	Unchanged
15/08/2007	8.0	Peru	7.28 (2664)	6.47 (2369)	-11.07	0.89	-119.42	-78.82	0.0009	3	Unchanged
12/09/2007	8.4	Sumatra	7.27 (2662)	6.44 (2358)	-11.42	0.89	-123.86	-55.66	0.0025	12	Unchanged
29/09/2009	8.1	Samoa Islands	7.97 (2918)	6.83 (2499)	-14.36	0.86	-192.85	-20.18	0.0067	16	Unchanged

27/02/2010	8.8	Chile	7.61 (2784)	6.19 (2265)	-18.64	0.81	-264.24	-45.37	0.0036	4	Negative
11/03/2011	9.1	Japan	6.15 (2251)	6.65 (2435)	8.17	1.08	92.87	25.34	0.0089	339	Unchanged

The most significant change in global volcanic activity associated with an earthquake occurred between December 2004 and April 2005 following a M_w 8.1 (Macquarie Islands, 23/12/2004) and M_w 9.1 (Sumatra, 26/12/2004) event, after which G_{VRF} more than doubled (Figure 2a). Although the largest calculated increase (141.87%) in G_{VRF} followed the M_w 8.1 earthquake, its occurrence just 3 days before the M_w 9.1 event means that this event was analysed rather than the M_w 8.1 earthquake. Within 75 days of the M_w 9.1 Sumatra earthquake (26/12/2004), G_{VRF} increased by 140.40%. Figure 2a shows that during the period December 2004 to April 2005, G_{VRF} increased exceeding $v + 1\sigma$ and resulted in a summed volcanic thermal emission of 196,265 MW (3% of the total radiated energy, 2000-2012). Interestingly, this initial increase was not sustained and 3 months after the event, G_{VRF} decreased to pre-earthquake radiant flux levels interspersed with short periods of increased G_{VRF} relating to eruptions at individual volcanoes (Fernandina, 14/05/2005 and Sierra Negra, 24/10/2005). The average number of active volcanoes also increased from N_b 4.60 to N_a 6.96 (51.28%, see Figure 3a) with new eruptions being detected at 10 volcanoes up to 19,200 km away. New periods of thermal activity at Barren Island, Fernandina, Karthala and Sierra Negra were noteworthy due to their long repose periods (previous eruptive activity in 1994, 1994, 1991 and 1980, respectively). On the basis of the β-statistic (454.00), change in G_{VRF} and the associated P_x (0.0001, based on a <0.005 significance), the increase in global volcanic activity is classed as significant, suggesting that the M_w 9.1 earthquake was temporally co-incident. Comparisons of change in G_{VRF} without an earthquake trigger, also provide additional evidence to support this temporally co-incident interaction, showing that a similar change in global volcanic activity only occurred in one other instance in the study period between May and July 2002, coinciding with an eruption at Nyamuragira (Democratic Republic of Congo).

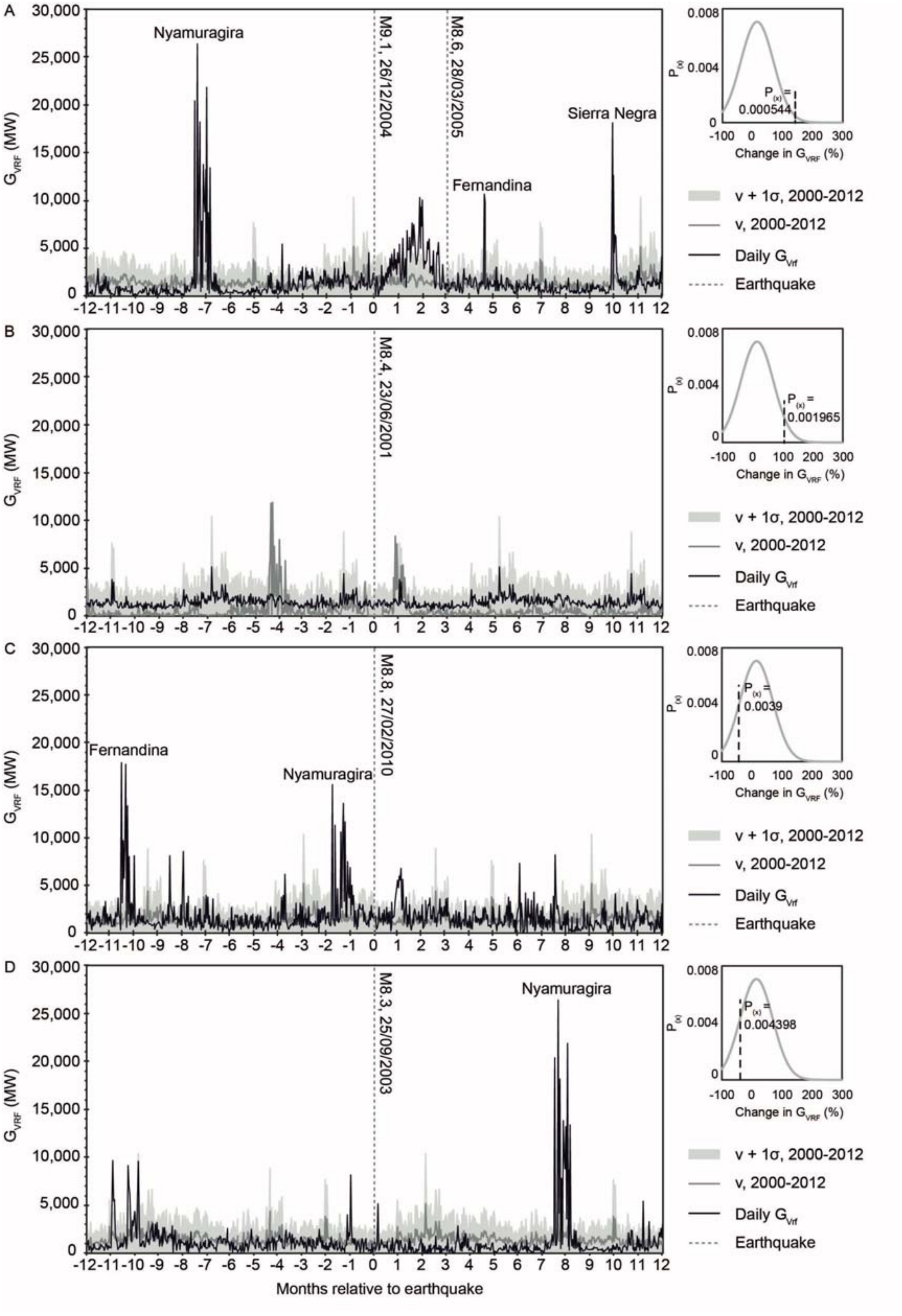

Figure 2 Daily volcanic radiant flux ±365 days relative to A) M_w9.1 Sumatra, 26/12/2004; B) M_w8.4 Peru, 23/06/2001; C) M_w8.8 Chile, 27/02/2010 and D) M_w8.1 Japan, 25/09/2003 earthquakes as compared to v (average radiant flux) and $v + 1\sigma$. Insets display the probability density function (P_x), which classifies the significance of the change in volcanic radiant flux.

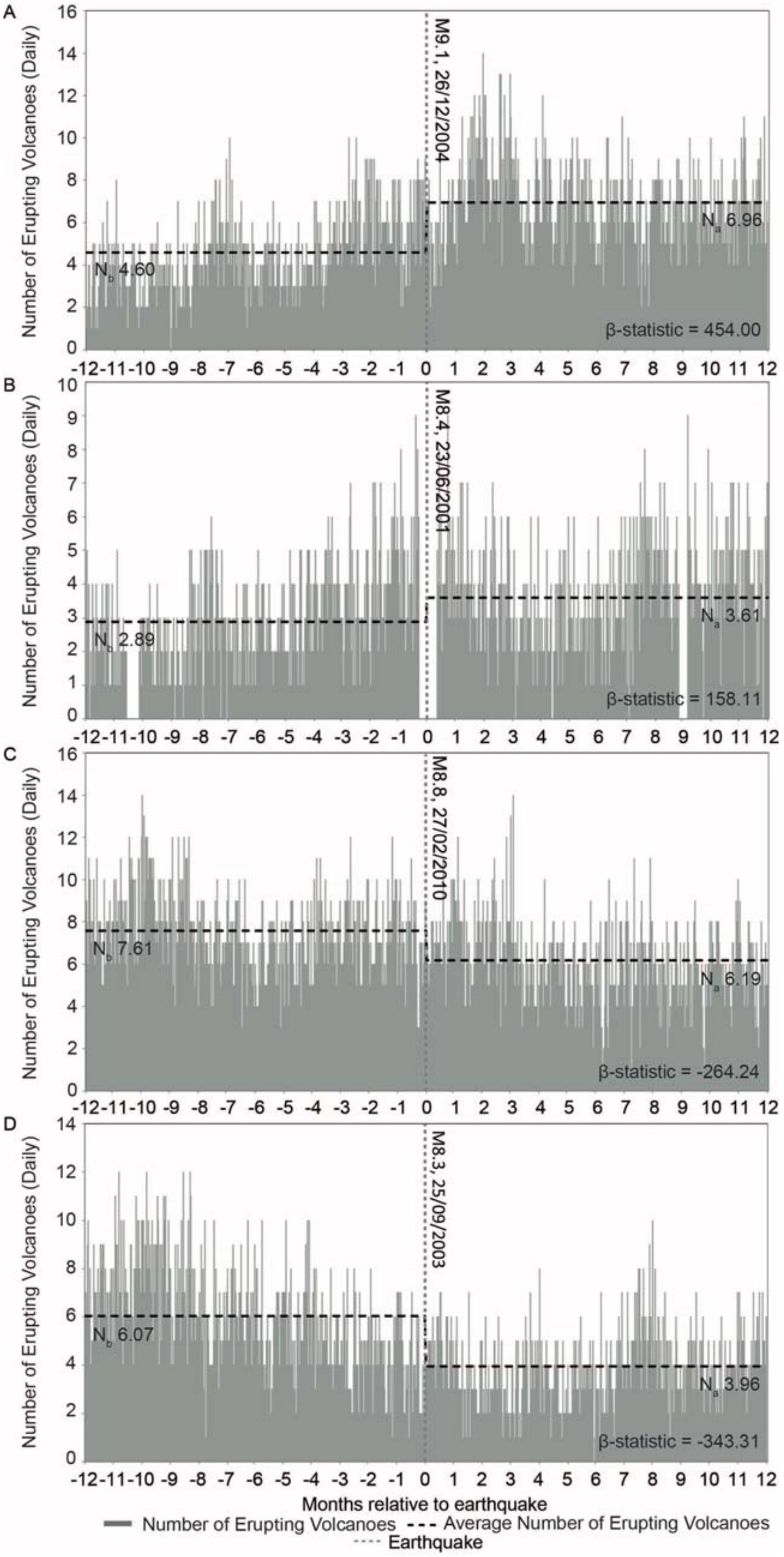

Figure 3 Daily number of active volcanoes ±365 days relative to A) M_w9.1 Sumatra, 26/12/2004; B) M_w8.4 Peru, 23/06/2001; C) M_w8.8 Chile, 27/02/2010 and D) M_w8.1 Japan, 25/09/2003 earthquakes.

Responses following the 2001 M_w8.4 Peru earthquake (23/06/2001) also exhibited an increase in global volcanic activity (up to 18,100 km) as well as identified an important characteristic that has not been previously identified. Figure 2b shows that in the year following the earthquake, G_{VRF} remained constant in-line with pre-earthquake thermal activity levels for the majority of the period. In fact, despite a small increase in G_{VRF} (104.38%, P_x 0.0010), the average G_{VRF} decreased from 633 MW before the earthquake to 528 MW after the event. In contrast, the average number of active volcanoes increased significantly (β-statistic 158.11) from N_b 2.89 to N_a 3.61 (Figure 3b). Critically, this demonstrates that in addition to volcanic radiant flux, the number of volcanoes experiencing thermal unrest is an important indicator of triggering following an earthquake. For example, while an earthquake may not trigger explosive volcanic eruptions it may be capable of initiating low-level thermal activity at a number of volcanoes, which also signifies an increased response of volcanoes to earthquakes.

Within 1 month of the M_w8.8 Chile earthquake (27/02/2010), G_{VRF} increased to more than 4,000 MW per day, relating to eruptions at Klyuchevskoy (29.24% of G_{VRF}), Eyjafjallajökull (25.69% of G_{VRF}) and Nyiragongo (14.69% of G_{VRF}) (Figure 2c). However, this initial response was short-lived and during the remainder of the year, G_{VRF} fell resulting in an overall decrease of 45.37% (P_x 0.0036). Corresponding with these findings, thermal activity ceased at 14 volcanoes with the average number of active volcanoes decreasing from N_b 7.61 to N_a 6.19 (-18.64%), Figure 3c. Notably, 6 months after the event, the lowest number of volcanoes experiencing thermal unrest was recorded (N_a 1.00). When compared to all $M_w \geq 8.0$ earthquakes, this temporally co-incident decrease in thermal activity is classed as significant based on the β-statistic (-264.24) and, as a result, confirms the ability of large magnitude earthquakes to inhibit global volcanic activity (up to 17,000 km) as well as enhance G_{VRF} following an event.

In the 365 days preceding the 2003 M_w8.1 Japan earthquake (25/09/2003), global volcanic thermal activity exhibited 452,704 MW of energy. With the exception of a short phase of thermal activity at Nyamuragira on 11/05/2004, following the event G_{VRF} decreased (-39.20%, P_x 0.0043) remaining below $v + 1\sigma$ and v for the majority of the period (Figure 2d). On the basis of the β-statistic -343.31, this event also experienced the most significant decrease in the number of active volcanoes from N_b 6.07 to N_a 3.96 (-34.64%, see Figure 3d) with activity ceasing at 13 volcanoes up to 18,000 km away.

Examination of the remaining $M_w \geq 8.0$ earthquakes did not identify statistically significant changes in global volcanic activity on the basis of the β-statistic and P_x (Table 1). Of the 9 events, 2 (M_w8.0 Tonga, 03/05/2006 and M_w8.3 Kuril Islands, 15/11/2006) experienced increases in G_{VRF} and 2 (M_w8.0 Peru, 15/08/2007 and M_w8.4 Sumatra, 12/09/2007) experienced periods of decreased activity. The largest increase (81.9%) in G_{VRF} followed the 2006 M_w8.0 Tonga earthquake (03/05/2006) and the largest decrease (-78.82%) followed the 2007 M_w 8.0 Peru earthquake (15/08/2007). However, the corresponding β-statistic (148.97 and -119.42, respectively) shows that the change in the number of thermally active volcanoes following these events was not significant. Of interest, the 2011 $M_w 9.1$ Japan earthquake (11/03/2011) observed no apparent thermal response. While other authors (e.g. Kato et al. 2013; Takada and Fukushima 2013) recorded triggered seismicity and deformation following this event, the largest change in G_{VRF} (25.34%) was relatively small and occurred 339 days after the event. Additionally, a low β-statistic (92.87) indicated that the change in the average number of active volcanoes was not significant.

4 Discussion

Overall, this research observed significant thermal responses at volcanoes in the year following large seismic events. The use of a globally comparable dataset of satellite-derived volcanic radiant flux shows that temporally co-incident changes in volcanic behaviour can include changes in activity at volcanoes that are already thermally active, induce new periods of thermal activity and inhibit thermal volcanic activity. In the majority of cases, the typical volcanic response involved a short period of modified activity followed by a return to pre-earthquake behaviour.

Volcanic responses associated with the 2004 $M_w 9.1$ Sumatra earthquake (26/12/2004) displayed the most significant increase in G_{VRF} and change in the average number of thermally active volcanoes during the study period. This observation supports previous research (e.g. West et al. 2005; Lemarchand and Grasso 2007; Walter and Amelung 2007), demonstrating potentially global relationships between large magnitude earthquakes and volcanic activity. Here, the difference in decay rates associated with the passage of seismic waves is key in identifying which stresses influence triggering (Manga and Brodsky 2006). Dynamic stresses, in particular, decay more slowly than static stresses ($1/r^{1.66}$ as compared to $1/r^3$, respectively) with distance (r) from the earthquake epicentre (Hill et al. 2002; Manga and Brodsky 2006) so it is more likely that triggering at the global scale can be attributed to dynamic stress change.

As mentioned, the occurrence of the $M_w 8.1$ Macquarie Islands earthquake (23/12/2004) just 3 days before the 2004 $M_w 9.1$ Sumatra event (26/12/2004) means that this event could have also influenced global volcanic activity. When considering the evidence for triggering associated with these events, therefore, it is clear that there are a range of factors that influence whether a response occurs. For example, the onset of an 11-minute earthquake swarm at Mount Wrangell (Alaska) one hour after the $M_w 9.1$ event (see West et al. 2005) demonstrates the occurrence of temporally co-incident volcanic activity and provides evidence to attribute the responses observed in this research with the $M_w 9.1$ event. In fact, West et al. (2005) stated that the earlier $M_w 8.1$ earthquake produced stresses one order of magnitude smaller than the M9.1 event (8.91×10^{23} J as compared to 2.82×10^{25} J, respectively), and did not trigger similar anomalous activity. Conversely, Manga and Brodsky (2006) suggested that a later M_w8.6 Sumatra earthquake (28/03/2005) was the trigger for new activity at Barren Island, Indonesia. Statistical assessments of change in G_{VRF}, P_x (0.0088, based on a <0.005 significance) and the β-statistic (137.06), however, determine that the changes associated with the M_w8.6 event were not significant (Table 1). This evidence also corresponds with Walter and Amelung (2007) who attribute the eruption of Barren Island, Indonesia to a transfer of stress south of the earthquake's epicentre that initiated a sequence of events including the M_w9.1 and M_w8.6 earthquakes. Despite this, there are instances of triggering which may be linked to the M_w8.1 event, including new thermal activity at Pacaya on 24/12/2004. Therefore, although the M_w9.1 earthquake was associated with unrest at a number of volcanic centres globally, some of those responses may actually be related to the earlier M_w8.1 or later M_w8.6 events or may be the result of a sequence of events.

The 2004 M_w9.1 Sumatra event (26/12/2004) also suggested the potential of earthquakes to influence new activity at previously quiescent volcanoes. This supports suggestions that an earthquake's capacity to influence volcanic activity may be dependent on an individual volcano's susceptibility to triggering (e.g. Linde and Sacks 1998; Hill et al. 2002; Bebbington and Marzocchi 2011). Most often, the passage of seismic waves relating to an earthquake are suggested to influence volcanoes in a critical state by advancing the onset of an eruption that would have occurred without an earthquake trigger. In particular, earthquakes cause a rapid change in stress (Manga and Brodsky 2006), so it is likely that volcanoes with long repose periods may be more sensitive to triggering. In the far field, mechanisms related to dynamic stress change, such as stress diffusion related to the elastic response of the lithosphere (Marzocchi 2002; Marzocchi et al. 2002), falling roofs (Hill et al. 2002; Manga and Brodsky 2006) and overpressure due to dynamic shaking (Linde et al. 1994; Hill et al. 2002), may influence the potential for triggering. The selective responses of volcanoes may then be controlled by a volcano's readiness to erupt, which would determine whether a response is observed (Hill et al. 1995; Husen et al. 2004; Prejean et al. 2004; Eggert and Walter 2009; De la Cruz-Reyna et al. 2010).

Importantly, this research also identified cases of decreased volcanic activity following an earthquake. Whilst such observations have been noted previously for both triggered seismicity (Sánchez and McNutt 2004) and volcanic degassing (Avouris et al. 2017), this is the first instance in which decreases in thermal volcanic activity have been recorded. The 2010 M_w8.8 Chile earthquake (27/02/2010) is particularly noteworthy as this event also resulted in instances of volcanic subsidence (Lupi et al. 2012; Mora-Stock et al. 2012; Pritchard et al. 2013). While different periods of unrest following earthquakes have been observed previously (e.g. Hill et al. 1995; Sánchez and McNutt 2004; Delle Donne et al. 2010; Pritchard et al. 2013; Avouris et al. 2017), decreased thermal activity alongside volcanic subsidence have not been reported. This suggests that stress changes following an earthquake can initiate different processes of unrest, which may result in different types of response being observed. In this instance, Pritchard et al. (2013) proposed that the north-south orientated volatile reservoir and faulting in the region was disturbed by either static or dynamic stresses causing subsidence. It is likely, therefore, that a similar process of co-seismic stress change and fluid release would cause decreased thermal activity due to decreased magma levels at the surface. Similarly, Sánchez and McNutt (2004) suggested that a volcano's location in relation to an earthquake's epicentre may also be critical, indicating that dynamic shaking around a volcano could create new cracks or open old ones promoting depressurisation. Therefore, this decrease in pressure could effectively inhibit volcanic activity due to perturbations on the volcanic system.

Earthquakes were also found to influence the number of erupting volcanoes as well as the volcanic radiant flux. When compared to the entire record for the study period, the average number of thermally active volcanoes remained constant before and after an earthquake whilst all temporally co-incident earthquake-volcano events were found to have a statistically significant change in the average number of active volcanoes. Other studies (e.g. Linde and Sacks 1998; Lemarchand and Grasso 2007; Delle Donne et al. 2010) have, indeed, shown a change in volcanic activity levels before and after an earthquake but most have failed to assess this statistically. This research, therefore, has important implications for the identification of triggered earthquake-volcano interactions as well as providing evidence to support instances of triggering and refute suggestions that these interactions may only reflect temporal correlations.

Given that this research has a number of variables, a key issue was to determine whether the activity observed is the result of a causal interaction or temporal co-incidence. To determine any association, statistical testing was used to evaluate the occurrence of large magnitude earthquakes alongside changes in volcanic radiant flux. This was done by using P_x to classify the significance of any change in volcanic radiant flux and the β-statistic to report the significance of the change in the average number of active volcanoes in standard deviations. Comparisons to a set of randomly generated values suggest that this approach was successful and provided useful information for the association of volcanic activity following large magnitude earthquakes. Finally, another issue that arose when considering earthquake-volcano interactions at a global scale was the influence of regional earthquake events. For example, regional earthquakes rather than the 2004 $M_w 9.1$ Sumatra event (26/12/2004) may have initiated new activity at 10 volcanic centres in 2005. Additional analysis, however, showed that in each case no other temporally co-incident earthquake ($M_w \geq 7.0$) within a regional proximity (< 1,000 km) was observed.

Based on the conditions defined here, the remaining earthquakes did not initiate a significant change in thermal volcanic activity. Despite this, all periods exhibited small variations in thermal volcanic activity within the range of baseline behaviour ($v + 1\sigma$). When considering these instances along with the temporally co-incident instances, it is important to note that all changes in behaviour occurred within the first 3 months (71.4%) or 9-12 months (28.6%) after the earthquake. This demonstrates that there may be a more complex interaction between earthquakes and volcanoes and, more detailed analysis of the temporal correlation at individual volcanoes may yield a clearer relationship, whether that is a two-way coupling as suggested by Eggert and Walter (2009) or the influence of earthquake-induced stresses on volcanic systems (Hill et al. 2002).

The limited thermal response following these seismic events further supports the argument that a number of controls on earthquake-induced volcanic activity exist. For example, following the 2011 $M_w 9.1$ Japan earthquake (11/03/2011) instances of triggered seismicity and deformation were recorded (Kato et al. 2013; Takada and Fukushima 2013), despite no thermal response being observed in this research. In contrast the 2010 $M_w 8.8$ Chile earthquake (27/02/2010) resulted in volcanic subsidence (Lupi et al. 2012; Mora-Stock et al. 2012; Pritchard et al. 2013) and decreased thermal activity. It is possible, therefore, that a volcano's location (Sánchez and McNutt 2004) and the associated changes (as a result of static or dynamic stresses) induced by an earthquake (Hill et al. 2002) may initiate different processes of unrest and different types of response may be observed. Equally, variations may be due to differences in each earthquake's characteristics (e.g. earthquake magnitude, depth, location, etc.) or an individual volcano's characteristics and critical state (i.e. readiness for response) (Hill et al. 2002; West et al. 2005; Eggert and Walter 2009). Given that this study considers global co-incidences, it is likely that mechanisms associated with dynamic stress change are favourable and that an earthquake's characteristics and a volcano's state are critical in determining a response.

5 Conclusion

This study has presented statistically significant instances of modified thermal activity following large magnitude earthquakes. Overall, both increased and decreased periods of activity were observed with typical responses involving a short period of modified activity followed by a return to pre-earthquake behaviour. Notably, in addition to changes in activity at active volcanoes, an earthquake is shown to be capable of influencing quiescent volcanoes and, therefore, modifying the number of active volcanoes at a global scale. The differing responses observed, however, suggest that there are a number of conditions and processes that may act following an earthquake. This observation, in particular, is critical to understand the parameters that result in earthquake-induced triggering, and further work is now underway by the authors to conduct more detailed analyses of the interactions at a regional scale as well as at individual volcanoes.

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Data Availability

Data can be found at MODVOLC: http://modis.higp.hawaii.edu and USGS Earthquake Catalog: https://earthquake.usgs.gov/earthquakes/search/.

Declarations of interest

None

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