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Key Points:

- Mafic effusive eruptions dominate the heat flux observed from Earth's volcanoes
- Ongoing Bardarbunga eruption is the most energetic effusive eruption since 2000
- Periodicity in thermal output observed at some volcanoes but not at others

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Some observations regarding the thermal flux from Earth's erupting volcanoes for the period of 2000 to 2014

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Abstract We present satellite measurements of the thermal flux observed from 95 active volcanoes, based on observations made daily over the past 15 years by NASA's Terra and Aqua Moderate Resolution Imaging Spectroradiometer sensors. Excursions from an apparent baseline level of thermal emission are attributable to episodic lava-flow-forming eruptions. Highest average intensity was associated with the July 2001 eruption of Etna, Italy, which radiated an average of 2.5×10^9 W over 23 days. However, recent fissure eruptions in the Afar Rift have attained higher average intensities of $2.4–4.4 \times 10^9$ W, albeit for days, not weeks. The largest magnitude eruption was the ongoing eruption of Bardarbunga, Iceland, which radiated 2.6×10^{16} J. Kīlauea, Hawai'i, has radiated the most energy since 2000, although the lava lake at Nyiragongo, Democratic Republic of Congo, comes a close second. Time series analysis reveals evidence for periodicity in radiant flux at some volcanoes but not at others.

1. Introduction

The thermal energy emitted by erupting volcanoes is a proxy for temporal variations in the intensity of those eruptions, having been demonstrated to correlate with the mass of lava required to yield that energy [e.g., *Harris et al.*, 1997, 1999]. Although this flux is difficult to measure in situ, Earth-orbiting satellites provide a convenient means to do so, from all of Earth's erupting volcanoes, and many studies have correlated at-satellite spectral radiance (or parameters derived from such measurements) with volcanic processes including volcanic gas emissions [e.g., *Wright et al.*, 2002a], lava effusion rates [e.g., *Harris et al.*, 1997], cycles of lava dome growth and explosive disruption [e.g., *Oppenheimer et al.*, 1993], and short-term variations in eruption intensity [e.g., *Harris and Thornber*, 1999].

Long time series of satellite remote sensing data are now available, from which decadal perspectives on the thermal behavior of all terrestrial volcanoes can be obtained. Using data acquired by the National Aeronautic and Space Administration's (NASA) space-based Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, we have estimated the total amount of energy radiated into the atmosphere by 95 volcanoes that erupted between February 2000 and 30 November 2014. We compare how these volcanoes differ with regards to the amount of energy they radiate and how the total amount of energy released varies with eruption style, specifically whether the volcano is characterized by the emplacement of mafic lava flows or felsic lava domes, the presence of persistently active mafic lava lakes, or vent-confined explosive activity.

2. Method

The raw data were obtained from the MODIS Volcano Thermal Alert System (MODVOLC) near-real-time thermal volcano monitoring resource (http://modis.higp.hawaii.edu; *Wright et al.*, 2002b). MODVOLC analyzes every pixel within every MODIS image that is acquired, providing complete global coverage in approximately 24 h and uses a simple multispectral threshold to detect which pixels within those images contain high-temperature radiators. For each pixel, the details of these "hot spots," including the geodetic location, observation time, and emitted spectral radiance at one midwave infrared (3.959 μm) and two long-wave infrared (11.03 μm and 12.02 μm) wavelengths, are recorded and reported at the aforementioned website. The nature of the relationship between temperature and spectral radiance means that although the spatial resolution of MODIS is coarse (1 km × 1 km), active lava bodies much smaller than this can be detected and quantified. Figure 1a ranks the 95 volcanoes for which MODVOLC has detected active lava during the period of 28 February 2000 and 30 November 2014, inclusive, by the total amount of energy they have radiated over that period.

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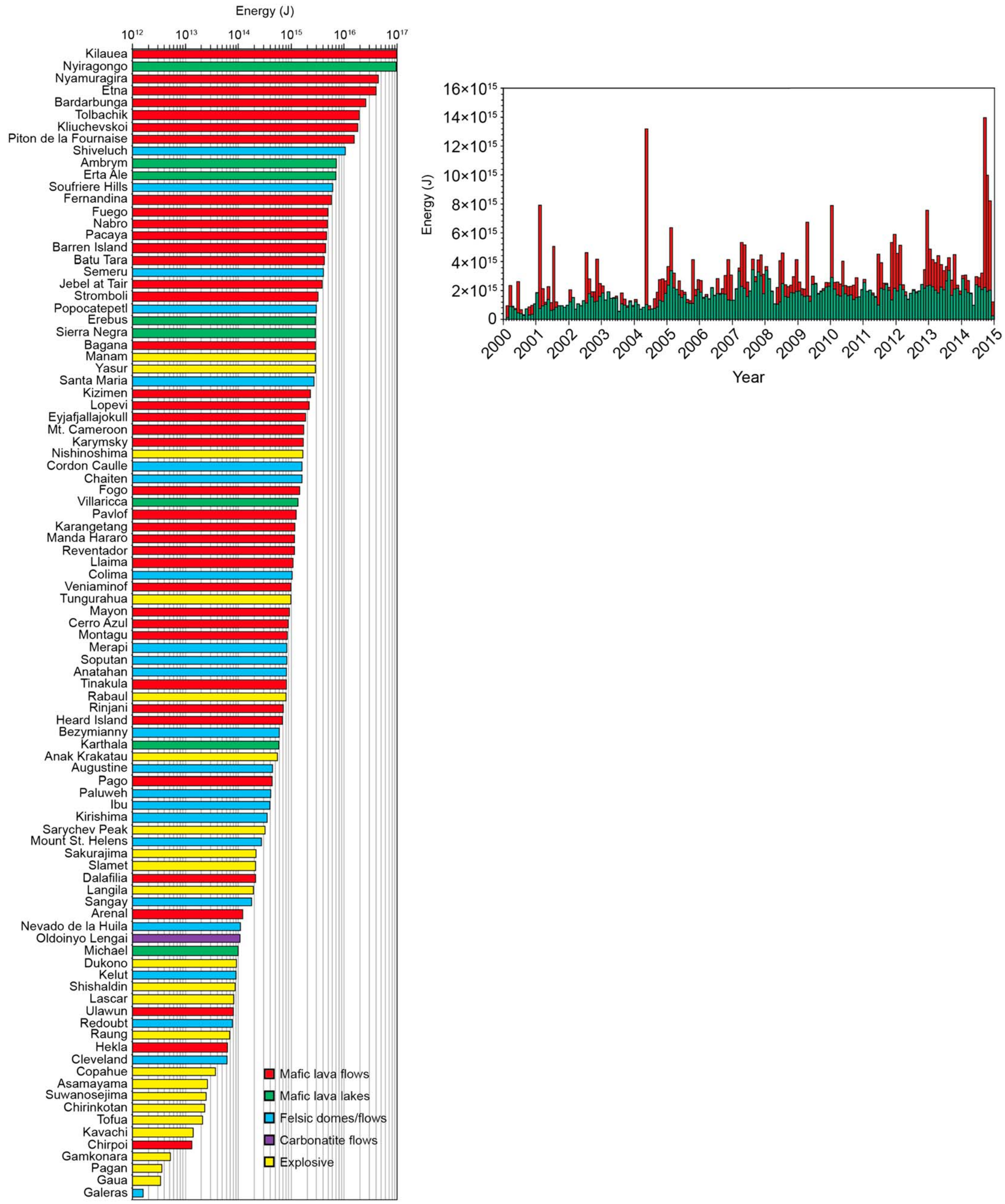

Figure 1. (left) Radiant energy output (J) from 95 volcanoes that have erupted during the period from 28 February 2000 to 30 November 2014. The style of activity responsible for the emissions has been classified, with red denoting the mafic lava-flow-forming eruptions, green denoting the mafic lava lakes, blue denoting the felsic lava domes, and yellow denoting the explosive activity. (right) Total energy output from all of these volcanoes (J) for each calendar month. The red bars denote the total energy, and the green bars denote the total energy minus the energy contributed by those volcanoes noted in the text.

The 3.959 μm spectral radiance emitted from each hot spot pixel ($L_{3.959\mu m}$, in W m^{-2} sr^{-1} μm^{-1}) is converted to an estimate of the radiant flux (in ϕ_e, in watts, or J s^{-1}) using the following relationship [*Wooster et al.*, 2003]:

$$\phi_e = 1.89\times10^7 \left(L_{3.959\mathrm{mm}} - L_{3.959\mathrm{mm,bg}}\right) \tag{1}$$

where $L_{3.959\mu m,bg}$ is the spectral radiance emitted from pixels adjacent to the hot spot and is used to account for the radiance emitted by ambient temperature surface within the hot spot pixels (given that the active lava bodies are usually subpixel in size). MODIS channel 22 is used when it is unsaturated, as it is more precise.

When it is saturated, equation (1) is solved using data acquired by MODIS channel 21, which is almost always unsaturated. For the rare instances when this channel was saturated (and for context, at Mount Etna, the incidence of channel 21 saturation was 0.02% from a total of more than 10,000 hot spots detected), the maximum measureable spectral radiance was used. This is $60\,W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$ for Terra-MODIS. No saturation was observed when using Aqua-MODIS, which has a much higher measurement limit of $93\,W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$.

By applying equation (1) to each hot spot in the database and summing for all hot spots observed at each volcano at each unique observation time, the radiant flux from all Earth's erupting volcanoes can be estimated on a near-daily basis. This was done by using MODIS data from both the Terra and Aqua spacecraft. *Wright and Flynn* [2004] used the MODVOLC data themselves to estimate the background term, $L_{3.959\mu m,bg}$. Here we use an independent estimate of background temperature obtained from the MODIS Land Surface Temperature product, where an average background value for each calendar month was determined from analysis of MOD11 (derived from Terra MODIS) and MYD11 (derived from Aqua MODIS) files for the 10 year period of 2000–2010, for each volcano. This method is preferable as the background temperatures estimated from this product are uncontaminated by spectral radiance from the lavas themselves and the effects of clouds. The uncertainty associated with each ϕ_e estimate is as much as ±30% (see *Zaksek et al.* [2013] for the details).

The application of equation (1) yields a time series of radiant flux (in watts or $J\,s^{-1}$) versus time, and integrating this yields the total amount of energy radiated (J). This integration was performed for each eruptive event at each volcano, where an individual event was considered to have ended if 7 days passed without a new hot spot observation. Only nighttime MODVOLC data were included in our analysis as these observations are uncontaminated by reflected sunlight or solar heating. As alluded to earlier, the data set does not include thermal emission from hydrothermal or geothermal expressions of volcanism as these are usually of insufficient temperature or size to exceed the MODVOLC detection threshold. The results we present document the radiant flux from volcanoes at which lava has been erupted.

Time series analysis was used to determine whether or not any periodicities were present in the radiant flux emitted by each volcano. This was based on an analysis of the amount of energy radiated at each volcano during each calendar month (i.e., J/month), mapped into the time and frequency domain using the wavelet transform. If periodicity is present in a time series, the wavelet transform [*Torrence and Compo*, 1998] provides information on which frequencies are dominant and when. Wavelet power spectra were computed for each volcano using the Morlet function. Significance level (90%) was determined against a red noise background spectrum.

3. Results

Figure 1a shows the total radiant flux calculated for all 95 volcanoes, classified by style of activity (summarized from reports published by the Smithsonian Institution's Global Volcanism Program and made available at http://www.volcano.si.edu/), while Figure 1b shows the total radiant flux from Earth's erupting volcanoes for each month since 2000. The data in Figure 1b can be divided into two components: a baseline radiant flux of $1–4 \times 10^{15}$ J/month, superimposed on which are large positive excursions, which are the associated with large, episodic, mafic lava-flow-forming eruptions, that can cause the global radiant flux to increase by a factor of 2 or 3. The red bars show the total flux from all volcanoes summed for each month. The green bars show the same value but with the contribution from Barren Island, Bardarbunga, Mount Cameroon, Cerro Azul, Dalla Filla, Etna, Eyjafjallajokull, Fernandina, Fogo, Hekla, Jebel at Tair, Kliuchevskoi, Manda Hararo, Nabro, Nyamuragira, Piton de al Fournaise, Sierra Negra, and Tolbachik (i.e., the principal volcanoes that have erupted large mafic lava flows episodically) removed. There is a subtle increase in this baseline level of emission over the period of 2000–2014, increasing from approximately 1×10^{14} to 2.5×10^{14} J/month over this period, an increase which, although subdued, is larger than the uncertainty in our approach. Much of this can be attributable to the ongoing eruption of Nyiragongo.

Episodic lava-flow-forming eruptions cause large departures from this baseline state. Regarding magnitude, the ongoing eruption at Bardarbunga, Iceland, is by far the largest to have occurred since 2000, so far radiating 2.6×10^{16} J, about one third more than the 2012–2013 eruption of Tolbachik, Russia (1.9×10^{16} J),

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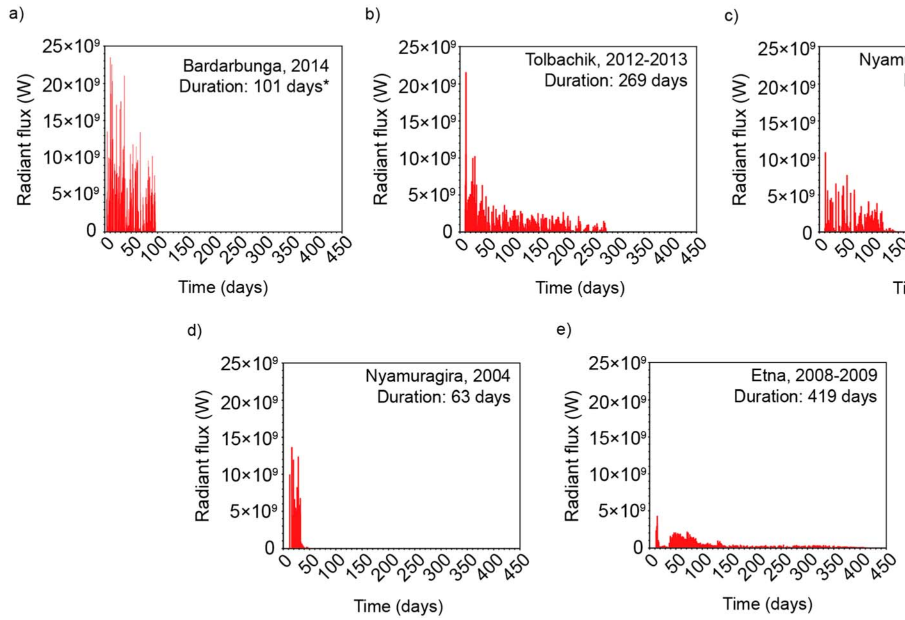


Figure 2. Radiant flux estimated for (a–e) the five episodic effusive eruptions of largest magnitude (with regards to total radiant energy output) in the time series. The Bardarbunga eruption is ongoing at the time of writing.

which itself radiated 50% more energy than the next largest, the 2011–2012 eruption of Nyamuragira. It is noteworthy that the Bardarbunga eruption has been ongoing for only 3 months (during which time approximately 1 km^3 of lava has been erupted), compared to the 10 month duration of the Tolbachik event (for which it took about 8 months to erupt 1 km^3 of lava [*Belousov et al.*, 2013]). Figure 2 shows the temporal evolution of radiant flux for the five largest effusive eruptions (in terms of total energy radiated) to have occurred since 2000. All display a rapid rise to a peak, followed by a longer waning phase, mirroring the evolution in volumetric lava effusion rate proposed by *Wadge* [1981] as being a characteristic of the elastic drainage of a magma chamber.

Figure 3 ranks the 20 largest effusive eruptions of the last 14 years using three metrics: total radiant energy yield (J; magnitude) and two measures of intensity, peak radiant flux, and eruption-duration-averaged radiant flux (both in watts). Bardarbunga, is the most remarkable effusive eruption to have taken place during the study period, exhibiting both the greatest total radiant energy and peak radiant flux. Although the 2012–2013 Tolbachik eruption has radiated substantially less energy than that observed at Bardarbunga, it is too conspicuous with respect to the other lava-flow-forming eruptions that have taken place during this study period (Figure 3a). These two eruptions, along with the 2002 Nyamuragira eruption, were characterized by peak radiant fluxes substantially higher than those recorded elsewhere. Of the seven eruptions to have occurred at Nyamuragira since 2000, five eruptions appear in Figure 3, making this volcano a particularly prodigious source of radiant energy. However, when averaged over the duration of the eruption (Figure 3c), the July to August 2001 eruption of Mount Etna ranks as having exhibited the highest sustained radiant flux over its 23 day duration (the ongoing Bardarbunga eruption exceeds the 2001 Etna eruption in terms of this average intensity metric but that eruption has yet to end). Of the four eruptions that have occurred at the Galapagos volcanoes since 2000, all were characterized by relatively high averaged intensities, being of relatively short duration (only the 2009 eruption of Fernandina continued for longer than 25 days). It is interesting to note that the radiant flux trends of three lava-flow-forming eruptions that have taken place in the Afar Rift in recent years (Figure 4a) are very different from those observed at other lava-flow-forming volcanoes. Radiant flux for these Afar eruptions shows a very rapid rise to a peak value (within a day or two of eruption onset) with no discernable waning phase, like those observed at Etna and Nyamuragira, with radiant flux falling precipitously to less than 5% of its peak within the first 5–10% of the eruption duration and continuing at very low levels until the end of the eruption. These differences likely reflect the different magma supply conditions governing the eruptions in these settings, that is fissure eruptions in a rifting environment versus intermittent drainage of a pressurized shallow magma chamber. If the long tail of these

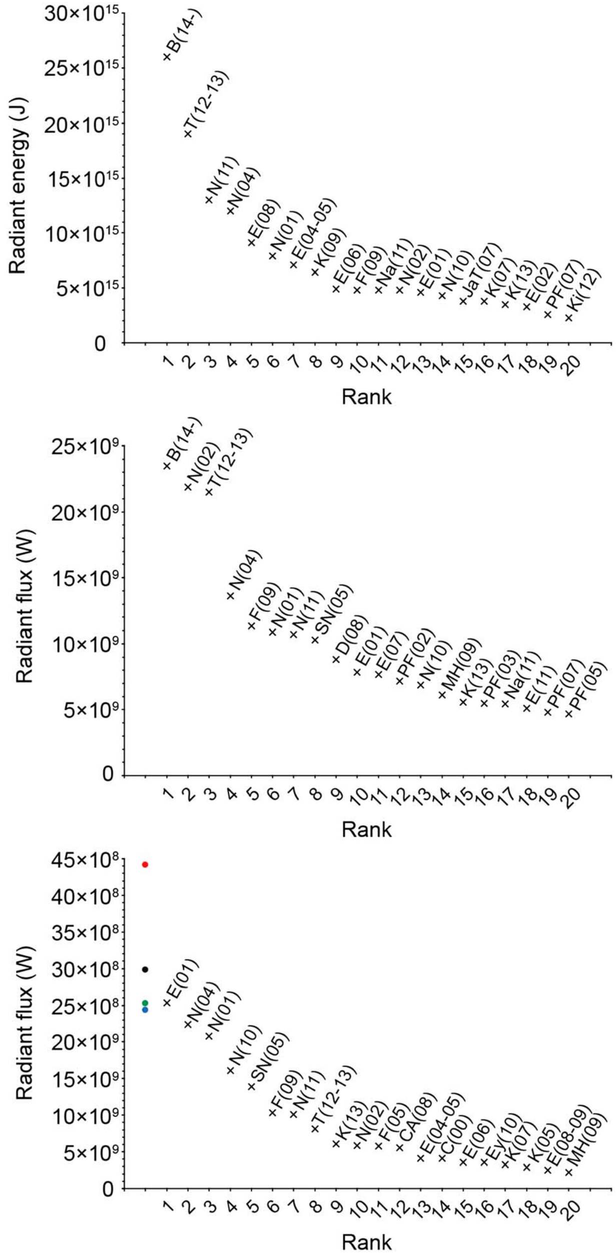
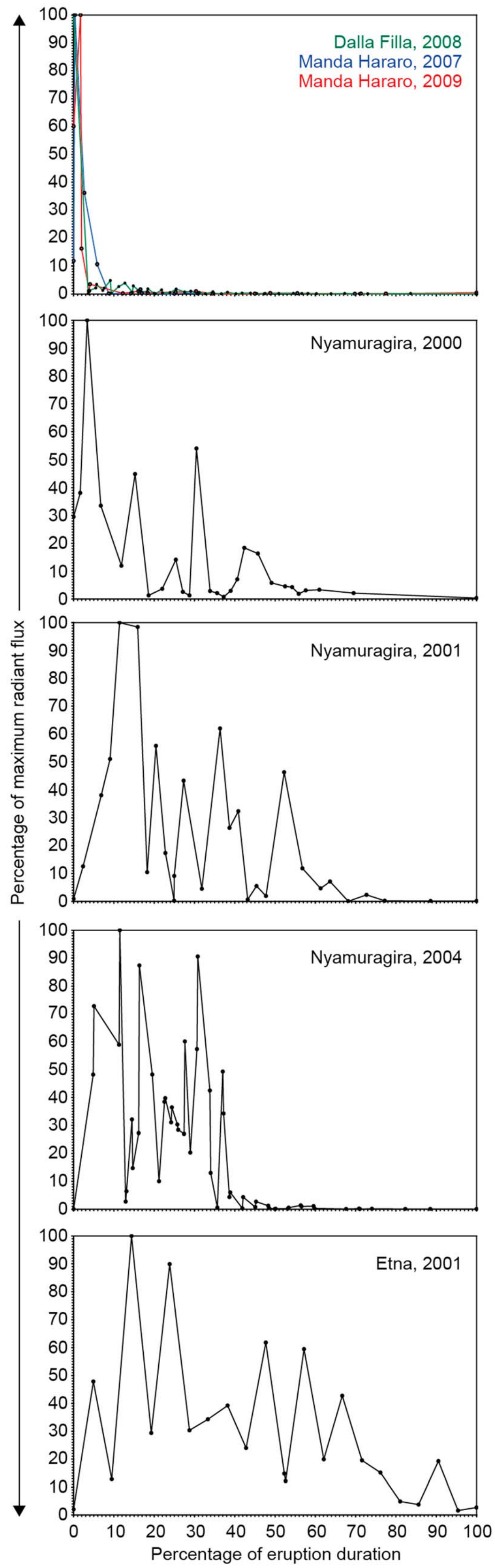


Figure 3. Eruptions ranked by (a) total radiated energy, (b) peak radiant flux, and (c) eruption-averaged radiant flux. Abbreviations: B–Bardarbunga, C–Cameroon, CA–Cerro Azul, D–Dalla Filla, E–Etna, Ey–Eyjafjallajokull, F–Fernandina, JaT–Jebel At Tair, Ki–Kizimen, K–Kliuchevskoi, MH–Manda Hararo, N–Nyamuragira, Na–Nabro, PF–Piton de la Fournaise, SN–Sierra Negra, and T–Tolbachik. In Figure 3c, the red, green, and blue circles on the left-hand side show the average radiant flux observed during the initial phases of eruptions at Dalla Filla (2008) and Manda Hararo (in 2007 and 2009), respectively. The black circle shows the average intensity of radiant flux observed for the ongoing Bardarbunga eruption.

radiant flux time series is ignored, the initial phases of these Afar eruptions constitute some of the most intense periods of activity observed in the last 14 years (Figure 3c).

Figure 1a shows that 37% of the total (4.9×10^{17} J) energy radiated by Earth's erupting volcanoes since 2000 has been via the episodic eruption of mafic lava flows at the 14 volcanoes noted earlier in this section. The ongoing Bardarbunga eruption amounts to ~6% of the total energy alone. Although the episodic effusive eruptions are the most intense events recorded in our time series, the total energy radiated in a relatively slow but steady manner by two persistently active volcanoes, Kīlauea, in Hawai'i (which erupts low effusion rate, primarily pāhoehoe flows), and Nyiragongo (which hosts an active lava lake) constitutes more than these 14 combined, accounting for 40% of the total global energy. Although Kīlauea has been the most prodigious volcano on Earth since 2000 in terms of radiant energy output (yielding 9.8×10^{16} J), the lava lake at Nyiragongo comes a very close second, emitting 9.5×10^{16} J. In summary, volcanoes that erupt mafic lava flows account for 67% of the estimated energy output over the past 14 years, with lava lakes contributing 23% (of which 90% is attributable to the exceptional Nyiragongo lake) and approximately 8% being the result of felsic lava-dome-forming eruptions. The small remainder is the result of vent-confined explosive activity, predominantly of the strombolian style.

Wavelet analysis of the radiant energy time series has been conducted to establish which, if any, volcanoes exhibit periodic variations in radiant output over the past 14 years. Although sampled at a nominal resolution of twice in a 24 h period, this is variable, being as low as twice every 48 h at the equator and higher toward the poles. For each volcano, the data were binned into monthly totals (i.e., energy output, in J/month), which were used as the basic unit for the time series analysis. Figure 5 shows some examples comparing spectrograms obtained for active lava flows, lava domes, and lava lakes, as well as that obtained for the output from all 95 volcanoes. With regards to lava-flow-forming eruptions, Etna exhibits strong and significant wavelet power at a scale of approximately 1.5 years between 2001 and 2010, whereas Heard Island shows strong and significant



power between 2000 and 2008 at the 3 year scale (although this does encroach upon the cone of influence). At Heard Island, there is also evidence for periodicity at the 3 to 6 month scale during each of its four eruptions between 2000 and 2014. The lava-dome-forming eruptions at Shiveluch yield strong and significant wavelet power at the scale of 2 to 3 years between 2001 and 2010, superimposed on which is significant power at a scale of less than 3 months throughout the time series. In contrast, the lava-dome-forming eruptions of Bezymianny, a volcano about 100 km to the south of Shiveluch, show no strong evidence of periodicity. The spectra for two persistently active lava lakes show no strong evidence for periodicity (some weak but significant power is revealed for two periods at Erta Ale and one period at Nyiragongo at the 3 to 6 month scale). At Nyiragongo, the radiant flux has increased secularly since the establishment of the lake in 2003 and 2010 before plateauing off. At Erta Ale, the radiant flux from its lava lakes has been much more variable. When considering the thermal flux from all 95 volcanoes since 2000, there is a weak band of spectral power over the entire time period at a scale of approximately 1.5 years. This feature is weak, however, and not deemed significant at the 10% level.

4. Conclusions

In terms of total radiated energy, peak radiant emission, and eruption-averaged radiant emission, the ongoing eruption of Bardarbunga in Iceland is the most remarkable eruption to have occurred on Earth in the last 15 years. Although episodic lava-flow-forming eruptions at mafic volcanic centers are much more intense sources of radiant energy over relatively short periods of time, the slow but steady eruption of lava at persistently active volcanoes is the largest source of radiant emission by Earth's subaerially erupting volcanoes. Kīlauea is the single largest source of radiant energy among the group of volcanoes we analyzed, justifying its unofficial title as the most active volcano on Earth. However, the lava lake at Nyiragongo has emitted almost as much energy since 2000. Evidence of periodic behavior at some volcanoes is also noted during periods of the 2000–2014 time series.

Figure 4. Radiant flux estimated for three recent Afar Rift eruptions, as well as three eruptions at Nyamuragira, and one at Etna. Here radiant flux is given as a percentage of the peak value observed during each eruption, while the abscissa is scaled to the percentage of the total eruption duration.

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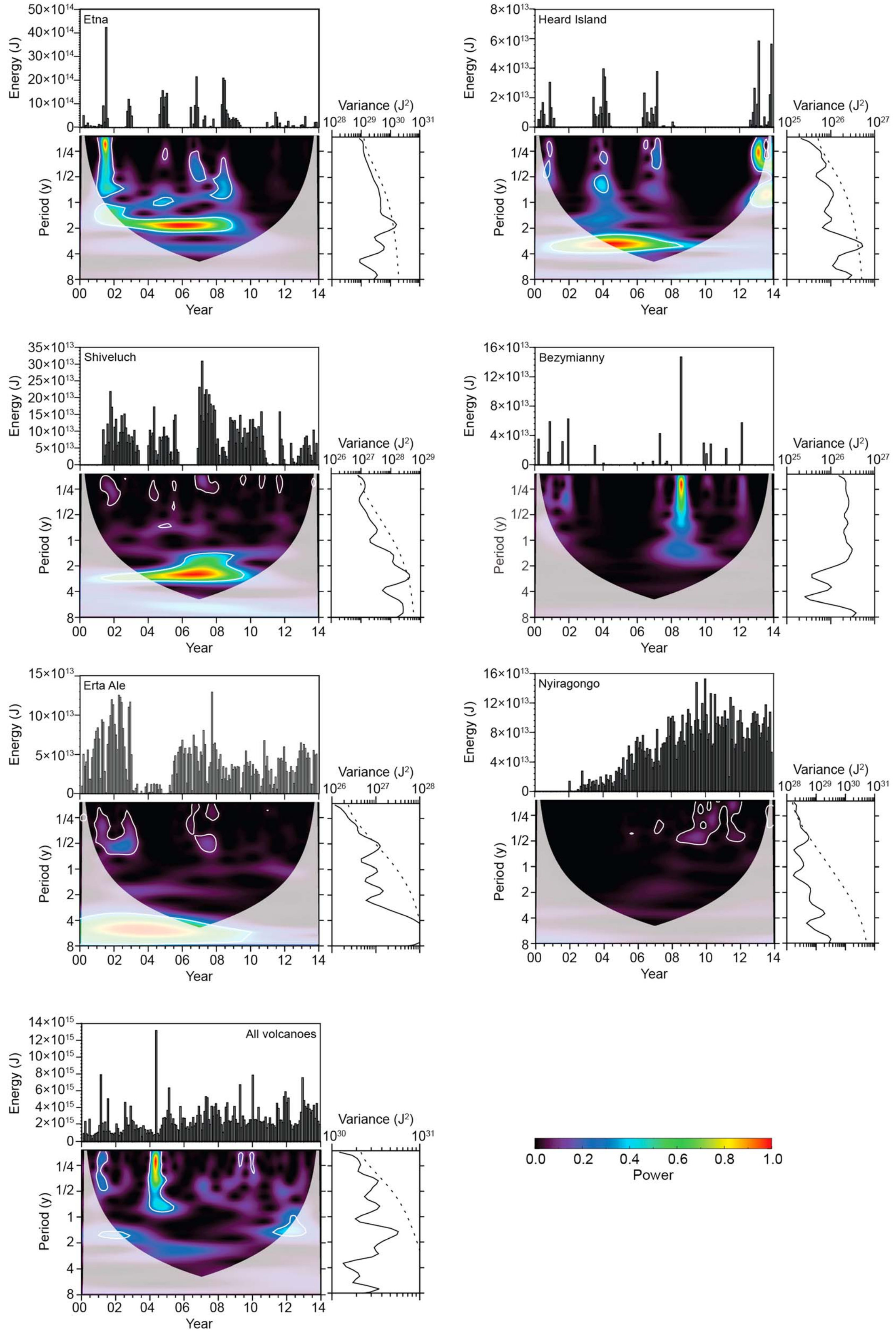

Figure 5. Wavelet power spectra (and time series from which they were calculated) for several volcanoes. Power is scaled in each case as percentage of the maximum wavelet power. The white contours are the 90% significance level. The graphs show the average wavelet power for each frequency (solid line) with 90% confidence limit (dashed line). The semiopaque polygon denotes the cone of influence, within which spectral content can be considered spurious.

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References

Belousov, A., M. Belousova, B. Edwards, A. Volynets, D. Melnikov, and S. Senyukov (2013), New cubic kilometer scale fissure eruption of Tolbachik, Kamchatka, Russia, *Geol. Soc. Am. Abstr. Programs*, *45*, 465.

Harris, A. J. L., and C. R. Thornber (1999), Complex effusive events at Kīlauea as documented by the GOES satellite and remote video cameras, *Bull. Volcanol.*, *61*, 382–395.

Harris, A. J. L., S. Blake, D. A. Rothery, and N. F. Stevens (1997), A chronology of the 1991 to 1993 Etna eruption using advanced very high resolution radiometer data: Implications for real-time thermal volcano monitoring, *J. Geophys. Res.*, *102*, 7985–8003, doi:10.1029/96JB03388.

Harris, A. J. L., L. P. Flynn, D. A. Rothery, C. Oppenheimer, and S. B. Sherman (1999), Mass flux measurements at active lava lakes: Implications for magma recycling, *J. Geophys. Res.*, *104*, 7117–7136, doi:10.1029/98JB02731.

Oppenheimer, C., P. W. Francis, D. A. Rothery, and R. W. T. Carlton (1993), Infrared image analysis of volcanic thermal features: Lascar Volcano, Chile, 1984–1992, *J. Geophys. Res.*, *98*, 4269–4286, doi:10.1029/92JB02134.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.

Wadge, G. (1981), The variation of magma discharge during basaltic eruptions, *J. Volcanol. Geotherm. Res.*, *11*, 139–168.

Wooster, M. J., B. Zhukov, and D. Oertel (2003), Fire radiative energy for quantitative study of biomass burning: Derivation from the BIRD experimental satellite and comparison to MODIS fire products, *Remote Sens. Environ.*, *86*, 83–107.

Wright, R., and L. P. Flynn (2004), Space-based estimate of the volcanic heat flux into the atmosphere during 2001 and 2002, *Geology*, *32*, 189–192.

Wright, R., L. P. Flynn, H. Garbeil, A. J. L. Harris, and E. Pilger (2002a), Automated volcanic eruption detection using MODIS, *Remote Sens. Environ.*, *82*, 135–155.

Wright, R., S. De La Cruz-Reyna, A. J. L. Harris, L. P. Flynn, and J. J. Gomez-Palacios (2002b), Infrared satellite monitoring at Popocatepetl: Explosions, exhalations, and cycles of dome growth, *J. Geophys. Res.*, *107*, doi:10.1029/2000JB000125.

Zaksek, K., M. Shirzaei, and M. Hort (2013), Constraining the uncertainties of volcano thermal anomaly monitoring using a Kalman filter technique, *Geol. Soc. London Spec. Publ.*, *380*, doi:10.1144/SP380.5.