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Fifteen years of thermal activity at Vanuatu's volcanoes (2000-2015) revealed by MIROVA

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Abstract

The Vanuatu archipelago consists of 80 islands and hosts 5 subaerial volcanoes (Yasur, Lopevi, Ambrym, Aoba and Gaua) that have shown sign of activity during the past decade. In this contribution we provide a 15 years-long datasets (2000-2015) of the thermal activity recorded at these active volcanoes by means of MIROVA (Middle InfraRed Observation of Volcanic Activity) a new volcanic hotspot detection system based on MODIS data. The analysed volcanoes are characterized by a spectrum of volcanic activities whose thermal signature has been tracked and carefully analysed . These include strombolian-vulcanian explosions at Yasur, lava flows at Lopevi, lava lakes at Ambrym, surtseyan-type eruptions within the Voui crater lake of Aoba and ash-dominated eruptions with strong degassing at Gaua. The collected data reveal several details of the long term eruptive dynamics at single sites such as a monthly long pulses in thermal emissions at Yasur volcano as well as at the two active craters of Ambrym (Benbow and Marum). Heating cycles within Aoba crater lake and intermittent pressurized eruptions at Lopevi volcano has also been detected and shed light in the eruptive dynamics of the analysed volcanoes. In addition we were able to track a two years long intensification of thermal output at Benbow crater (Ambrym) that preceded the occurrence of the first intra-caldera eruptions of this volcano since 1989. We emphasize how the data provided by MIROVA represent a new, safe and affordable method for monitoring in near-real time a large spectrum of volcanic activities taking place at Vanuatu and other volcanic areas.

1 - Introduction

Vanuatu archipelago is a Y-shaped chain of Pacific islands, extending about 1200 km in the North-South direction between the Equator and the Tropic of Capricorn. The archipelago lies along the New Hebrides, on the edge of the Pacific plate that is obducting over Indo-Australian Plate (Fig.

1a). Seismic and volcanic activity in Vanuatu are closely related to a tectonic setting associated to active subduction (Pellettier et al., 1998; Calmant et al., 2003). Earthquakes and eruptions may directly affect nearly 250.000 inhabitants who populate the archipelago.

A total of 8 volcanoes have shown intense volcanic activities within the last century with eruptions causing partial and/or entire evacuation at some the villages (Global Volcanism Program Database). In particular, at least 5 volcanoes have been considerably active during the last 15 years (Aoba, Ambrym, Lopevi, Gaua and Yasur; Fig. 1) making Vanuatu arc as one of Earth's prominent sources of volcanic degassing (Bani et al., 2012). A sixth submarine volcano, named East Epi, and located on the seafloor between Epi and Lopevi islands (Fig. 1), erupted in early March 2004 (Global Volcanism Program, 2004a). However, we does not include this eruption in our analysis since its submarine nature make the approach used in our analysis not adequate (see method).

Vanuatu archipelago is also a unique natural laboratory for observing and studying a large variety of volcanic activity. Because of its intra-ocean setting, the volcanism is essentially basaltic (MacFarlane et al., 1988; Peate et al., 1997) but characterized by eruptive styles ranging from strombolian-vulcanian explosions (i.e. Yasur) to effusive eruptions (i.e. Lopevi) and Ambrym is currently hosting two nearly-permanent lava lakes which is a rather unique case in the world. Moreover, the summit of Aoba volcano hosts one of the largest active crater lakes in the world, whilst Gaua volcano is well known for its intense solfataric activity impacting the surrounding areas. In this context, thermal remote-sensing is providing a new tool for monitoring contemporaneously different types of volcanic activities, and the acquired data can be successfully processed and compared with those acquired from other ground-based monitoring networks. In this paper, we present the thermal activity recorded over these five active volcanoes during 2000-2015 period. In particular, we analyze the data retrieved by a new volcanic hot spot detection system, named MIROVA (Coppola et al., 2015a), which is based on the analysis of MODIS (Moderate Resolution Imaging Spectroradiometer) infrared data. After describing the method and presenting the results (only nighttime data) we will discuss the thermal output recorded by MIROVA between 2000 and 2015, in the light of the observed-reported volcanic activity at Vanuatu. Thus, we carefully discuss the thermal emissions at single volcanoes and we carefully analyze their long-term trends providing the basis for further thermal monitoring at Vanuatu islands.

Figure 1

2. Background

On the 8 Vanuatu's volcanoes exhibiting volcanic activity in the last century, only 5 apparatus (Yasur, Lopevi, Ambrym, Aoba and Gaua) showed sign of subaerial volcanic activity since 2000 (Global Volcanism Program Database). In this section, we summarize the main geological and structural features characterizing these volcanic centers and, particularly, discuss their recent and current volcanic activity, as well.

2.1 Yasur

Yasur volcano (19.53°S 169.442°E), is located on the SE sector of the Tanna island, within the 9x4 km Siwi caldera (Fig 1b). Together with the Yenkahe dome (on the western edge of the caldera) the 361 m high pyroclastic cone forms the "Yasur–Yenkahe volcanic complex", a unusual example of persistent explosive activity (at Yasur cone) and a rapidly uprising resurgent block (at Yenkahe dome; Peltier et al, 2012; Nairn et al., 1988; Merle et al., 2013). Volcanic activity at Yasur has been already reported by Cook and D'Entrecasteaux explorations (Aubert de la Rue, 1960; Nairn et al., 1988) and has been persisting, in its current form, for the last 630–850 years (Firth et al., 2014). The current eruptive style typically spans from strombolian to vulcanian explosions, with rare occurrences of lava flows (Carney and MacFarlane, 1979; Nabyl et al., 1997). Erupted lavas and tephra are trachy-andesite and display a limited compositional range with SiO_2 contents spanning between 55.2– 56.6 wt% (Firth et al., 2014). Based on tephra accumulation rates, a uniform, time-averaged eruption flux of ∼410–480 m^3 $days^{-1}$ has been inferred by Firth et al., (2014). Continuous degassing is related to the persisting activity of Yasur, with estimated SO_2 emissions of ∼630-680 t day^{-1} (Metrich et al., 2011; Bani et al., 2012)

2.2 Lopevi

Lopevi (16.507°S 168.346°E) is one of the most active volcanoes of the Vanuatu archipelago, characterized by a conical-shape island 7 km wide and 1413 m high (Fig 1c). Historical activity seems to have occurred along a NW-SE fissure trend cutting the volcano summit. The recent lava and pyroclastic flows take place within the western sector of the island where is also located the current active crater, (formed during the 1963 eruptive phase; Warden, 1967). Eruptive styles spans from explosive to effusive activities, emitting lavas and tephras with basalt to basaltic-andesite compositions (SiO_2 = 50.6 – 52.4 wt%; Beaumais et al., 2013). Notably, the 1939 and the 1960 eruptions caused the evacuation of the island (Global Volcanism Program Database). Starting from 1960, eruptions have been taking place every 3-5 years that some authors grouped into 15-20 years long eruptive cycles (Beaumais et al., 2013). At least, six eruptive periods have been reported since 2000 (Global Volcanism Program Database). Sulfur output estimated during recent eruptive phases approaches 1000 t d^{-1}, while passive degassing measured on February 2006 indicates emissions up to 150 t d^{-1} (Bani et al., 2012).

2.3 Ambrym

Ambrym basaltic volcano (16.25°S 168.12°E) is one of the most active volcano of the Vanuatu Arc. The basal shield volcano is topped by an exceptionally large cone, surrounding a 12-km-wide summit caldera (Robin et al., 1993). Post-caldera activity was dominated by the Marum and the Benbow intra-caldera cones, ~3 km distant from each other, which have frequently hosted distinct lava lakes with persistent degassing and strombolian activity (Bani et al., 2012, Allard et al., 2015). Effusive eruptions also occurred in historical times and were mainly focused outside the caldera, along a rift zone oriented N 105 (Robin et al., 1993). Three sub-craters are exposed within the Marum cone (named Mbwelesu, Niri Mbwelesu and Niri Taten), while a unique crater characterize the Benbow cone. In recent years both structures hosted an almost persistent lava lake activity (Rothery et al., 2005), with passive degassing mainly characterizing Benbow crater, and strombolian explosions frequently observed at Marum crater (Allard et al., 2015). A common basaltic magma (50.5 %wt SiO2; cf. Allard et al., 2015) seems to supply the degassing of both craters, though different CO2/SO2 ratio (1.0 and 5.6-3.0, for Benbow and Marum, respectively) is attributed to distinct gas-melt separation depth driving the activity at the surface (Allard et al., 2015). Reported pulsatory phases and exceptionally high degassing rate, (releasing up to 20 kT/day of sulfur dioxide during extreme events; Bani et al., 2012) makes Ambrym among the most powerful volcanic gas emitters on Earth (Allard et al., 2015). An extraordinary high supply rate of 25 m^3 s^{-1} has been inferred on the basis of the SO2 flux and the magma S content (Allard et al., 2015). Notably, a minor flank eruption (the first since 1989) occurred on February 21st, 2015 from a new vent opened in the summit caldera (cf. http://www.geohazards.gov.vu/).

2.4 Aoba

Aoba island (also named Ambae; 15.4°S 167.83°E) represents the emerged part of the most voluminous basaltic shield volcano of the Vanuatu archipelago, an edifice 3900 m high (1546 m a.s.l.) with a volume of about 2500 km^3 (cf. Bani et al., 2009a). The caldera summit hosts two main crater lakes (Voui and Lakua), formed 400 years ago during a major post-caldera explosive event (Global Volcanism Program database). The acidic Voui lake (pH ~ 2) is one of the largest worldwide crater lake, measuring 2 km in diameter with a surface area of 2.12 Mm^2 (cf. Bani et al., 2009a). Notably, Aoba is considered one of the most dangerous volcano of the Hebrides Arc, because of the potential occurrence of major phreatic eruptions similar to those that occurred in the past (Robin et al, 1995). The recent erupted material includes olivine-rich basaltic lava flows and a variety of pyroclastic deposits (Warden, 1970). On 21 November 2005, an increase of 5 °C was observed in lake Voui suggesting a precursory increase in magmatic degassing into the lake (Nemeth et al., 2006). Few days later a new eruptive phase started and was characterized by phreatomagmatic explosions, and the ejection of hot pyroclastic materials, mud and steam of gas. The activity culminated in mid-December after which a 100m height island hosted an hot lake inside it. On late December field observer noted that small-scale eruptions continued in Lake Voui which suddenly changed colour from blue to red in May–June 2006 (Bani et al., 2009b).

2.5 Gaua

Gaua island (14.27°S 167.5°E) is a composite basaltic volcano characterized by a large summit caldera (6x9 km) occupied by the Letas crater lake (cf. Bani et al., 2012). Parasitic cones, which rim the caldera, testifying the Pleistocene activity characterized by lava flow, that in several cases reached the coast of the island. Recent activity is concentrated on the SE cone of Mt. Garat that lay in the center of the Letas Lake (cf. Fig. 1f). Reactivation of the Gaua occurred on 1962, when periodic ash emissions from central crater were reported until the 1977. Successively, the craters inside the Mt. Garat was characterized by solfataric and fumarolic activity (Global Volcanism Program, 1999a). On late September, 2009, a new eruptive phase required the evacuation of a large number of the inhabitants of the E sector of the island toward the villages of the W part.. Gaua is actually in state of seismic unrest coupled by continue sporadic explosions and strong degassing (Global Volcanism Program, 2011a; Global Volcanism Program, 2013a).

3 - Method

MIROVA is a near real time volcanic hot spot detection system based on MODIS infrared data (Coppola et al., 2015a). This system combines an high efficiency in detecting small hotspot (~1 MW), and a moderate spatial (1 km^2) and temporal (4 images per day, 2 nightime and 2 daytime) resolution that enable to locate and quantify the heat sourced by a variety of volcanic activity.

Original MODIS granules are analysed automatically according to five principal steps. These are: (i) data extraction, (ii) cropping and resampling into 50x50 km box centred on the volcano summit (iii) definition of Region of Interest (ROIs), (iv) hot-spot detection and finally (v) calculation of the "excess" of MIR radiance and Volcanic Radiative Power (VRP) (see Coppola et al 2015a., for details in the processing scheme of MIROVA).

Volcanic Radiative Power is calculated by using the MIR method (Wooster et al., 2003) according which for any individual alerted pixel, the VRP is calculated as:

$$VRP_{PIX} = 18.9 \times A_{PIX} \times (L_{4alert} - L_{4bk}) \qquad \text{(eq. 1)}$$

where A_{PIX} is the pixel size (1 km^2 for the resampled MODIS pixels), L_{4alert} and L_{4bk} are the 4 μm (MIR) radiance of the alerted pixel/s and background, respectively. The coefficient 18.9 has been empirically calculated by Wooster et al., (2003) in order to fit the linear relationship between MIR radiance and radiative power. When two or more pixels (a cluster of pixels) are alerted, the total radiative power is calculated as being the sum of each single $VRP_{PIX.}$

According to Wooster et al., (2003) the MIR method allows the radiative power to be calculated with an error of ±30% if the effective temperature of the sub-pixel radiator is between 600 and 1500 K. However, in the case of cooler hotspots the radiant power calculated via the MIR method provides only a minimum boundary of the whole thermal output, and more likely represents the heat radiated by the hotter portion of the emitter (Coppola et al., 2015a).

4 - Results

The Volcanic Radiative Power recorded at the five analysed volcanoes between 2000 and 2015 is shown in Fig. 2 (nigh time data).

In order to display the high number of detections, ranging from 1 MW to more than 1 GW, we first plotted all the time-series on logarithmic scales (Fig. 2).

Figure 2

As shown in Fig. 2 the analysed volcanoes display a large variety of thermal emissions, in terms of intensity, frequency distribution, temporal persistence and overall patterns. Before discussing in more details the VRP time-series and their volcanological aspect (next chapter), below we summarize the main features of the recorded datasets including their general trend, frequency of alert detection, thermal levels and open- to closed-vent behavior (with the meaning given by Rose et al., 2013). We thus compared our bulk results with those of MODVOLC algorithm (Wright et al., 2002) whose robustness provide a first qualitative validation of our datasets.

4.1 Yasur

Thermal output of Yasur (Fig. 2a, left panel) was persistent during the analysed period, typically oscillating between 10 and 100 MW, and reaching values above 100 MW only in few occasions after 2008. Notably, the log-transformed data display an unimodal dispersion, peaking at 16 MW and maximum values at 190 MW (Fig. 2a right panel). Thermal activity has been almost continuously detected during the whole analysed period, with 50% and 99% of the alerts occurring within 2 and 20 days, respectively. This suggests a well-established open-vent structure with the meaning that the magma within the feeding system was almost persistently exposed to the atmosphere. The overall frequency of alert detection was 22.3%.

4.2 Lopevi

Lopevi volcano produced the highest thermal anomalies detected over Vanuatu between 2000 and 2015 (Fig. 2b). In particular thermal levels above 100 MW have been reached several times, although their temporal persistence was relatively low (few weeks at the most). The detected thermal signal at Lopevi is remarkably episodic, with weekly- or monthly-long periods of activity, interrupted by months or years characterized by the absence of thermal anomalies. The episodic nature of Lopevi thermal emissions is quite clear in the timeseries shown in Fig. 1c, 2b, where we recognize at least 10 distinct episodes of eruptive activity (detailed in the next chapter). Notably, since early 2007, there have been no thermal anomalies detected by MIROVA. This represents the longest resting period of Lopevi (8 years) since the beginning of our dataset. The log-transformed data display a bimodal dispersion, thus suggesting the existence of at least two distinct thermal regimes (Coppola et al., 2012, 2014), separated at about 50-100 MW (Fig.2b right panel). The overall frequency of alert detection was 2.3%.

4.3 Ambrym

Thermal activity at Ambrym volcano has been almost continuous between 2000 and 2015 oscillating essentially between 10 and 300 MW (Fig. 2c). A clear outsider (about 4000 MW) was detected on February 21st, 2015 (associated to the first effusive activity), and will be discussed later. The Volcanic Radiative Power (log-transformed data) display a wide distribution without clear peaks, but with equally recurrent detections between 10 and 100 MW (Fig. 2c right panel). Similarly to the Yasur volcano, about 50% of the alerts occur within 2 days, with only 1% of the alerts occurring after more than 20 days without thermal anomalies. The longer period without thermal detections was recorded between October 22nd, 2005 and April 13rd, 2006 (176 days). The overall frequency of alert detection was 17.2%.

4.4 Aoba

Between 2000 and 2015 thermal anomalies at Aoba volcano were recurrently detected by MIROVA (Fig 2d) with a unimodal distribution peaking at about 2 MW (Fig. 2d right panel). The radiant power oscillated almost exclusively between 1 and 10 MW, with few exceptions (> 10 MW) on November 2005 as well as on 2012 and 2013. The mean repose time between two consecutive alerts is 13 days and the overall frequency of alert detection is 4.5%.

It is important to note that the radiant power provided by MIROVA, calculated via the MIR method (equation 1), represents a robust estimate of the heat radiated by hot targets having an integrated effective temperature higher than 600 K. As it will be discussed later, in the case of large crater lakes (>0.1 km^2), such as Voui crater lake, the "excess" of MIR radiance at the base of the MIR method, could be due to the contrast between the lake temperature and its surroundings (see next chapter). Hence, the timeseries shown in Fig. 2d must be taken with caution and considered as a qualitative proxy of the thermal activity of Aoba volcano between 2000 and 2015.

4.5 Gaua

A total of 96 alerts have been detected over Gaua volcano between 2000 and 2015 (Fig 2e). Thermal anomalies were systematically below 5 MW with the exception of three alerts, on early 2010, that peaked at 24 MW on March 28th , 2010. The mean repose time between two consecutive alerts was 79 days.

4.6 Limits and uncertainty of the data provided by the MIROVA system

Coppola et al., (2015a) outline that a number of issues must be taken into account when using the data provided by MIROVA. These includes the detection of false alerts, the effects of clouds, volcanic plumes, and variable viewing geometry, as well as the uncertainty in the radiant power calculation (see Coppola et al., 2015a for details). In particular the authors underline that single data points provided by MIROVA cannot be trusted without a visual inspection of the image, since there is, as yet, no robust method to evaluate automatically the amount of thermal radiation attenuated by clouds, or volcanic plumes. Here, we have not checked manually the large number of images processed at the five volcanoes (more than 50000 images) with the exception of few cases related to the effusive activity of Lopevi (section 5.2) and Ambrym (section 5.3) volcanoes, as well as to the few hotspots detected at Gaua volcano (section 5.5) . However, also without manual check of each single image, the general trend depicted from the timeseries still provide essential information on the thermal activity operative at the observed volcano especially when evaluating the timeseries on a, monthly- or yearly-long timescale. This is the case of radiant flux recorded over Vanuatu's volcano (Fig 2) where the variations in the thermal output are analysed and interpreted on the above-mentioned timescales, where the meteorological effects are negligible.

A first order validation of MIROVA data has been obtained by comparing the annual alerts (nighttime) detected at each volcano with those recorded by the MODVOLC algorithms (which use the same MODIS images, but with a fixed threshold to detect hotspots; Wright et al., 2002). The results are summarized in Table 1. While for the high energetic eruptions of Lopevi (often above 100 MW) the two systems perform almost similarly, the adaptive algorithm of MIROVA produce a general improvement in the number of alerts detected at Ambrym and Yasur volcanoes, both characterized by recurrent detections between 10 and 100 MW (cf. Fig. 2). The high efficiency of MIROVA is particularly evident at Aoba volcano where the persistent thermal anomalies between 1 and 10 MW (Fig. 2d) are never detected by MODVOLC (Fig. 3d), due to its high automatic threshold that does not allow to detect such small thermal anomalies.

On the other hand the visual inspection of Gaua images where hotspot(s) has been detected suggests that the most of these alerts are uncertain. All the hotspots detected at Gaua are located on the summit of the volcano where Mt. Garat and Letas crater lake are present. However, the fact that the alerts have persistently radiant power < 5 MW (with the exception of three alerts on 2010) and that differently from Aoba, they appear mostly during the warm season (December- March) without being associated to any evident trend or reported activity make these detections potentially false. Note that a limited number of "false" detections (typically less than 2% of the total MODIS overpasses), may be eventually triggered by the MIROVA algorithm in absence of any sign of volcanic activity (Coppola et al., 2015a). Accordingly we may consider the thermal signal recorded at Gaua volcano as a background noise of the MIROVA system. In contrast, the genuine thermal alerts detected in early 2010 has a clear volcanic origin and will be discussed later.

Table 1

5 - Discussion

5.1 Mild explosive activity at Yasur volcano

Yasur has exhibited continuous strombolian and vulcanian activities at least since the time of Captain Cook's visit in 1774 (Firth et al., 2014). The timeseries of radiant power shown in Fig. 3 provides clear indication of the thermal emission produced by this open-vent activity during the past 15 years. Notably, our dataset suggests that between 2002 and 2015 the bulk thermal output of

Yasur was characterized by a persistent increase of about 0.8 MW per year, punctuated by several pulsating phases. In particular, at least seven main monthly-long periods of enhanced thermal activity can be distinguished on the timeseries, each one culminating at 50-150 MW and followed by decreasing trend up to the baseline (Fig. 3a). The analysis of the background MIR radiance recorded on the summit of Yasur (Fig. 3b) allowed us to discard the hypothesis of meteorological or seasonal effects on the observed thermal pulses. On the other hand, Bani and Lardy (2007) suggest that high degassing phases and cyclical patterns, usually lasting more than a month, have been also inferred at Yasur from continuous seismic monitoring since 1991 (Global Volcanism Program Database, 1999b). Accordingly, it is likely that the cyclical thermal activity shown in Fig. 3a likely characterized periods of higher strombolian activity, with lava bombs, dense ash plumes from multiple vents, and elevated SO_2 levels followed by intervals when explosions are less powerful and less frequent. Field reports provide us evidences of increased activity during the observed thermal cycles, as for example in August 2002, June 2004, January 2010, May-June 2011, and May 2013 (Global Volcanism Program Database, 2004; 2010; 2011b).

Coppola et al. (2012, 2014) suggested that the thermal output recorded at open-vent volcanoes characterized by strombolian activity, such as Stromboli, is not directly related to the explosion rate itself, but rather to the size, number and temperature of the active vents. These elements, are effectively controlled by the fluctuations of the magma level within the shallow conduit which in turn may modulate the explosive activity at the surface (leading eventually to episodes of sustained spattering, fountaining and outflows). In a similar manner, the variations in the thermal output recorded at Yasur (Fig. 3a) can be likely related to cyclic fluctuations of the magma level regulating the number, size and temperature of active vent(s) and more generally feeding the explosive activity at the surface.

At open-vent volcanoes the main control on the lava level, is the reservoir pressure resulting from the balance of supply and eruption rate to and from a shallow reservoir (Patrick et al., 2015).

However, shallow gas-driven processes, such as those characterizing strombolian activity (i.e. ascent of gas slug or gas pistoning) as well as instabilities within the plumbing system (i.e. narrow conduits, changes in the gas volume fraction, magma density and viscosity), may also produce perturbation of the magma column with fluctuations of the summit lava level on a time scale spanning from minutes to days or months (Witham et al., 2006; Carbone et al., 2014).

In absence of any evidence of a long term change in the density of magma supplied at Yasur (i.e. due to changes in temperature, exsolved gas content, crystal content, dissolved water content, etc), we suggest that the 15 years long rising of thermal output, observed since 2002, could be related to a slow increase in the magma pressure within the feeding system of the volcano. On the other hand the observed fluctuations of thermal emission may be related to cyclic oscillations of the magma column eventually associated to the monthly-long degassing phases reported by Bani and Lardy (2007). A multidisciplinary characterization of magma degassing and explosive activity at Yasur volcano will better clarify the source of the observed thermal trends.

Figure 3

5.2 Effusive eruptions at Lopevi volcano

Between 2000 and 2007 the thermal activity at Lopevi has been intermittent, showing clusters of thermal anomalies separated by periods of rest lasting months or years (Fig. 4). Notably, after the first half of 2007 no more thermal anomalies have been detected by MIROVA. This pattern suggests that during the analysed period Lopevi volcano behaved more likely as a closed-vent system, whereby magma reached the surface only during intermittent eruptions (Rose et al., 2013). However, the bimodal distribution of radiant power (Fig. 2b right panel) indicates the presence of two thermal regimes (separated at about 100 MW) that may be related to distinct types of eruptive activity (cf. Coppola et al., 2012, 2014). In particular a low thermal regime (< 100 MW) was characterized by a series of clustered anomalies detected between February 2004 and April 2005 (Fig. 4b), whereas an high thermal regimes (> 100 MW) characterized all the other periods of more intense activity (Fig 4a).

At Stromboli volcano such kind of bimodal distribution has been associated to distinct thermal regimes, likely representing the strombolian to effusive activity, respectively (Coppola et al., 2012, 2014). Two main evidences suggest that the distribution of thermal detections at Lopevi volcano also define similar kinds of activities. Firstly, the clusters of low thermal anomalies were detected during a period during which a plume rising from Lopevi have been occasionally reported but no effusive activity was never observed (Global Volcanism Program Database, 2005, 2007a,b). This occurred, for example, during late September 2004 when explosive activity were heard by villagers in S Ambrym (Global Volcanism Program Database, 2005) in correspondence of a cluster of low thermal anomalies detected by MIROVA (Fig. 4b). The second evidence relies on the fact that all the anomalies characterizing the low thermal regime were located in correspondence of the summit craters, and do not extend along the flank of the volcano (as effectively observed in the case of the detections belonging to the high thermal regime). Based on these evidences we thus suggest that the low thermal regime (< 100 MW) typically characterize phases of mild explosive activity occurring at the summit craters of Lopevi, while the high thermal regime (>100 MW) characterize periods of effusive activity along the flank of the volcano, eventually accompanied by mild or stronger explosive activity.

Figure 4

Our data reveal that between 2000 and 2007 at least 6 main periods of effusive activity (high thermal regime) occurred at Lopevi. Based on the trend that typically characterize each period, we classify these effusive eruptions into 3 distinct typology (Table 2).

The eruptions occurred on May 2006, June 2006 and April 2007 (Fig. 4c), clearly show a waxing-waning trend, typical of pressurized closed system (Wadge, 1981). These events last from 24 to 33 days, and produce peaking radiant power, ranging from 1170 MW to 1896 MW. According to Harris et al., 2000 we classify these trends as *Type I*, whereby the eruptions take place within a pressurized system, resulting in a rapid increase in effusion rates, followed by a slow waning phase as pressure decreases. Nonetheless, all these eruptions where accompanied by important explosive activity with ash plumes reaching an altitude of 2-5 km (Global Volcanism Program Database, 2007b).

Table 2

Differently, the eruptions of March-July 2000 and October 2005-January 2006 show a rather steady trend that persisted for 121 and 100 days respectively, with an almost stable thermal output amounting to 200-300 MW (Fig. 4d). Few observations, reported during these eruptive periods, suggest the presence of ash plume rising to an altitude of 2-5 km (Global Volcanism Program Database, 2000; 2005). Following Harris et al., 2000, we classified these trends as *Type II* whereby the steady effusion may result by non-pressurized overflow from the summit craters.

Finally, the eruptions occurred on June 2001 and June 2003 belong to a separate group since they were characterized by very short durations (5-7 days each) and peaks in thermal emissions that reached 783 and 729 MW, respectively. Notably, these eruptions were accompanied by stronger explosions that generated ash plumes rising up to 8-12 km as well as large debris avalanches resulting from a partial collapse of the active cone (Global Volcanism Program Database 2001; 2003). The extremely pulse-like character of these eruptions, and their association with strong explosive activity allowed us to classify them as *Type IV* trend, which according to Harris et al., 2011 likely relate to the rise and eruption of rapidly ascending magma batches.

The data and classification presented above clearly enhance a compound eruptive dynamics that characterized Lopevi volcano between 2000 and 2007. However, since late 2007 MIROVA did not detected other thermal anomalies, thus suggesting that Lopevi entered into a period of rest. The April 2007 eruption (*Type I* trend) produced the highest thermal anomaly of the whole dataset, and likely marked the end of a cycle of frequent eruptions.

5.3 New effusive activity and cyclic oscillations at Ambrym lava lakes

The detailed timeseries of the thermal output recorded at Ambrym volcano is shown in Fig. 5a. The most evident feature of this dataset is the long-lasting cyclic thermal activity, oscillating between 10 and 300 MW (discussed later), drastically interrupted on February 21, 2015 by the highest nighttime thermal anomaly recorded since 2000 (3537 MW). This anomalous high thermal peak was produced by the first effusive eruption occurring at Ambrym volcano since 1989 (Global Volcanism Program, 2015). The combined analysis of nighttime and daytime MODIS images (Fig 6a-e) suggests that the effusion of lava started surely after February 20th (14:30 UTC; Fig. 6a) since at that time the thermal anomaly (67 MW) was still associated to the activity at the two craters, Benbow and Marum. However, on February 21st (02:40 UTC) an high thermal anomaly (5953 MW) extending on the southern part of the caldera suggest that an effusive eruption was ongoing within the summit caldera and had already reached its climax (Fig. 6b). In the following hours the effusion gradually waned (Fig. 6c and 6d) and by February 23rd (02:30 UTC), the radiant flux recorded by MIROVA had already dropped to 75 MW (i.e to pre-eruptive level) likely suggesting that the eruption was essentially over (Fig. 6e). Interestingly, by this time there were no signs of thermal activity within the Benbow crater, while two hotspots were still visible within the Marum crater (Fig. 6e). A cluster of hot pixel also defined the location of the cooling lava field that was localized about 3 km south of the Marum crater (Fig. 6).

The availability of thermal data recorded during this event allowed us to convert the VRP into estimates of Time Averaged lava Discharge Rate (TADR; Coppola et al., 2013):

$$TADR = \frac{VRP}{c_{rad}} \qquad \text{(eq. 2)}$$

where TADR is in m^3s^{-1}, VRP is in W, and c_{rad} is the radiant density, expressed in J m^{-3}.

The radiant density approach (eq. 2) relies on the fact that under a given discharge rate, basic, intermediate and acidic lava bodies radiate thermal energy differently because of their different bulk rheology (Coppola et al., 2013). In particular, the authors suggest that the radiant density of a lava body can be predicted (± 50%) on the basis of the silica content of the erupted products:

$$c_{rad} = 6.45 \times 10^{25} \times \left(X_{SiO_2}\right)^{-10.4} \qquad \text{(eq. 3)}$$

where X_{SiO2} is the silica content (wt%) of the erupted magma. For Ambrym basalts, here we used a silica content of 50.5 wt% (Allard et al., 2015), and we calculated a radiant density of 1.2 (±0.6) × 10^8 J m^{-3}. The resulting effusive trend (Fig. 6f) indicates a short-lived waxing-waning eruption, peaking at 64 (±32) m^3 s^{-1} and producing a total erupted volume of 4.8 (±2.4) Mm^3.

Figure 5

A post-eruption Landsat 8 image, acquired on 24th March 2015, allowed us to locate and map more accurately the new lava field that reached a maximum extension of about 2.2 km^2 (Fig. 6g). The lava field was composed by two main lava flows, ~6 km long each, that were erupted from an eruptive fissure-vent located about 3 km south of Marum Crater (at max elevation of 780 m asl; Fig. 6f). The visual inspection of this image suggests that the eruptive fissure could be 500-1000 m long and oriented N 60 (i.e radial from Marum crater), but further field observations are required to confirm this feature.

Based on the previous estimates of intra-caldera lava flow thickness (1-3 m; Robin et al., 1993) the extension of the 2015 lava field yield a total erupted volume of 4.4 (± 2.2) Mm^3 in very good agreement with the MODIS-derived estimates. We thus calculated a minimum eruption rate of 27.3 ± 13.7 m^3 s^{-1} by assuming a maximum duration of the eruptive events of 44 hours based on MIROVA data; Fig. 6a-e).

It is worth noting that the new effusive eruption was preceded by a low but persistent increase of the thermal activity (Fig. 5a). In fact, since 2013, the radiant power increased for the first up to 350 MW on January 2013, and reached more than 400 MW on December 2013, 500 MW on April 2014 and more than 550 MW on January 17, 2015, about one month before the effusive eruption. These data suggest that the increase in the thermal output recorded since 2013 clearly tracked an ongoing pressurization phase of the plumbing system possibly culminated into the eruption of February 2015.

Because of the 1 km spatial resolution of MODIS we were able to discriminate and quantify the heat flux radiated by the two Marum, (Fig 5b) and Benbow (Fig 5c) active craters before the eruption, and to compare their activity on a timescale of several years. These data suggest that the anomalous intensification of thermal emission that preceded the eruption (i.e. 2014-2015) was mainly due to the gradual increase of activity at the Benbow crater (Fig. 5c), although the Marum activity was already at high levels, but similar to those recorded since 2010 (Fig. 5b). This feature might suggest that the new intra-caldera eruption was associated to the gradual pressurization of the N 105 rift zone, over which the new vent and the Benbow crater are aligned (Fig. 6g). On the other hand, this preferential direction is not consistent with the orientation of the new eruptive fissure inferred from the Landsat image which seems to radiate from the Marum crater (Fig. 6g), thus suggesting a complex plumbing system beneath the active craters of Ambrym.

Such a complexity is also revealed by the thermal dataset that indicates an unstable, pulsating and convecting magma column modulating the recent activity at both craters also prior the effusive eruption.

The first long cycle (2000-2005) occurred on both craters with similar intensity and trend (reaching peaks in thermal emissions up to 100-200 MW at both craters; Fig. 5b and 5c). Differently, the shorter cycles observed in 2007 and 2008, occurred almost exclusively within the Marum crater, while the thermal activity within Benbow remained more stable and at lower level (20 MW). Between 2009 and 2012 a further long lasting cycle was mainly observed at the Marum crater, although a small increase (from 20 to 50 MW) has been also observed on Benbow. On the opposite, the increase in thermal emissions observed in 2013 was principally due to a new phase of intensified activity at Benbow that somehow affected, only moderately, the activity at Marum. Finally, during the 2 years that preceded the eruption both the craters were extremely active (above 100 MW), but with the Benbow showing the gradual increase discussed above. It is thus clear that the cycles of magma rise and fall that control the thermal emissions affected a single crater at a time, or occasionally both. Again, this is indicative of the occurrence of a complex dynamics taking place within the shallow magmatic system of Ambrym.

As discussed for Yasur's case, the causes of the variation in the magma level within the shallow conduit(s) are generally associated to pressure changes (balance of supply and eruption rate to and from a shallow reservoir ; Patrick et al., 2015) or magma density changes (associated to shallow degassing processes). We have not sufficient data to better characterize the eruptive dynamic of Ambrym's craters. However, the recognition of an increasing trend at Benbow crater before the recent eruption (Fig. 7), coupled with the waxing-waning effusive trend, typical of pressurized system (Wadge 1981) could suggests that cyclic pressurizations of the shallow plumbing system were at the origin of the cycles observed at Benbow crater. Similarly to what has been observed at Stromboli volcano (Coppola et al., 2012, 2014) the rising of the magma column (and the consequent increase in thermal emission) presaged the effusive eruptions of Ambrym, with a threshold of about 500 MW (10 times higher than at Stromboli), anticipating the hazardous changes on the volcano activity (Fig. 5 and 7). Similarly, the thermal oscillations recorded at Marum crater could be eventually driven by the same pressurization phases controlling the Benbow activity (as for example during 2000-2005). However, they could also reflect some more complex process taking place within the plumbing system of Marum and related to a more efficient gas-melt separation that characterize the very shallow dynamic of this crater (Allard et al., 2015).

Figure 6

In this regard, it is interesting to note that the contribution of Marum to the total thermal output of Ambrym (we excluded the eruption on this calculation; Fig. 7) amounted to 63% (~4.9×10^{15} J), while the activity within the Benbow crater produce the resultant 37% (~2.9×10^{15} J). This partitioning is somehow opposite to the SO_2 output according which the Marum cone produces 35% of the overall emissions, while Benbow only 65% (Allard et al., 2015). The activity within the two craters is thus characterized by a remarkably different sulfur vs thermal emission, with Benbow crater providing much more SO_2 per unit of radiant flux (about four times more than Marum).   This could suggest that sulfur and heat magma budgets of lava lakes (cf. Oppenheimer et al., 2004) not necessarily follow the same trend, with the first (sulfur) sampling the rate of magma supplied within the shallow degassing cell and the second (heat) sampling the rate of magma reaching the free surface. In this regards, closed- (Benbow) versus open-system (Marum) degassing processes (Allard et al., 2015) may also play an important role in modulating the intensity, rate and extension of magma convection and the amount of heat radiated into the atmosphere.

Such a comparison is preliminary and based on punctual gas measurements (Allard et al., 2015) that not necessarily represent the bulk degassing conditions operative during these last 15 years of activity (as effectively the long-term thermal output do). On the other hand, we cannot rule out other external factors that may have influenced the radiant heat detected at the two craters. Among all a different crater morphology that may make more difficult to detect the bottom of Benbow crater with respect to Marum. Further detailed investigations of crater morphologies coupled with synchronous thermal and degassing analysis at both craters will probably help to better understand the complex dynamics of these extremely active volcano.

Figure 7

5.4 Heating episodes at Aoba crater lake

Between 2000 and 2015 Aoba volcano experienced a series of volcanic phenomena that include several crater lake heating cycles, major surtseyan eruption on November 2005, a limnic event on 2006 and minor explosive activity on 2011-2013

The whole timeseries recorded at Aoba between 2000 and 2015 is shown in Fig. 8, where at least six distinct phases have been distinguished on the basis of the observed thermal activity.

Figure 8

A first clear long-lasting pulse (hereby ascribed to an heating cycle; phase I) has been detected during 2000-2002 (Fig. 8). Thermal output increased through 2000 and culminated in January 2001 when ~11 MW were detected. Then thermal anomalies over the summit of Aoba gradually decreased during 2001 and almost disappeared in late 2002. Between 2003 and late 2005, thermal anomalies over Aoba were substantially low (phase II), showing a tendency to reduce to less than 1 MW from early 2004, up to late 2005. On 6 September 2005, MIROVA detected an hotspot amounting to less than 1 MW thus suggesting that by that time the thermal state of the lake was almost at its background level. The following period (November 2005-September 2006) coincides with a major eruptive phase (phase III) which leads to the occurrence of several volcanic phenomena, including surtseyan activity, phreatic explosions, small-scale explosive activity, strong degassing and a limnic episode that produced a spectacular color change of the lake in May-June 2006 (Nemeth et al., 2006, Bani et al., 2009b). On 21st November 2005 a bulk temperature anomaly of the lake surface of 5 °C was measured by Bani et al., (2009b) thus suggesting a precursory increase in magmatic degassing into the lake. Although the first sub-aerial eruptive activity was reported on 27 November 2005 (Global Volcanism Program, 2005b), our data suggest that two days before, on 25 November (at 14:10 UTC), Aoba volcano had already entered into an eruptive phase (Fig. 8). On this day we detected the highest thermal anomaly of the whole dataset (~21 MW), likely associated to the beginning of phreatomagmatic and surtseyan activity (Global Volcanism Program, 2005b). Since this date, we noticed a period of frequent thermal anomalies which however declined with time, reducing to 5-10 MW on December 2005, 3-5 MW on March-April 2006, and finally 1-2 MW between June and August 2006. Notably, the SO_2 measurements performed during this period do not show such a waning trend, but conversely they increased through time passing from 16-24 kg s^{-1}, during the eruptive climax (late November-mid December 2005), up to 21-43 kg s^{-1} on June-August 2006 (Bani et al., 2009b). During 2007 another minor heating cycle is evident in our data and produced a new, long-lasting minor pulse (phase IV). This was followed by a period of lower but more frequent thermal anomalies which were persistently detected between 2008 and 2010 (phase V). This suggests that some kind of activity was still ongoing and that the crater lake temperature was almost continuously above normal values. This is consistent with the high SO_2 release detected up to four years after the eruptive episode (Bani et al., 2012). Starting from late 2010 a new important phase of thermal activity appears in our dataset (phase VI in Fig. 7) that culminated in December 2011 and persisted at high levels during 2012. This period was characterized by more frequent alert detections which declined only after January 2013 (Fig. 7). Notably, field observations are indicative of higher activities: since 2011 reports described the occurrence of several episodes of ash fall around the crater, small-scale explosive events and phreatic explosions throughout 2012-2013 (Global Volcanism Program Database, 2013a). These observations support the fact that intense thermal anomalies (above 10 MW) were likely associated to a persistent sub-aerial activity, that was also observed several years earlier (e.g., during December-January 2006).

In order to better validate the thermal trend recorded by MIROVA over Aoba volcano in Fig 8 we compared the radiant power with the temperature anomaly (DT) of the Voui crater lake estimated by Alain Bernard for the period 2000-2007 (Bernard, 2009; http://www.ulb.ac.be/sciences/cvl/aoba/Ambae1.html; red squares in Fig. 8). In particular, the author used several ASTER images (90 m resolution in the TIR bands) to calculate the temperature difference between the active Voui crater lake and its neighbor Lakua lake, filled by freshwater. This procedure allowed Bernard (2009) to infer the occurrence of multiple heating cycles (i.e. 2000-2002, 2005-2006, 2007-2008) characterizing the Voui crater lake, in close agreement with the trend drawn by the MODIS-derived VRP. The excellent correlation between the two datasets supports the observations made by MIROVA also after 2008, and suggests the occurrence of a further important phase of activity during 2011-2013 likely culminated into small explosive events and major phreatic explosions.

The close agreement between the MIR-derived VRP (MODIS) and the TIR-derived DT (ASTER) could be eventually due to the occurrence of unreported high-temperature gas emissions that accompanied the heating cycles of the lake (i.e. fumarole fields and/or hot degassing vents along the coast). Alternatively, it is possible that given the large dimension of the lake (more than one MODIS pixels) the "excess" of MIR radiance at the base of VRP calculation was directly related to the contrast between the lake temperature and the surroundings. In this circumstance the absolute values of the radiant power shown in Fig. 8 must be taken with caution since they only provides minimum estimate of the real heat flux radiating from the lake surface.

Besides, these results suggest that MIR data, largely used to detect high-temperature thermal anomaly related to lava flows, lakes or domes, cold be also adequate to detect smaller scale thermal activity such as fumarole fields and eventually temperature variations operative over large crater lakes.

5.5 Explosive activity at Gaua volcano

As described previously, the most of the low thermal anomalies (<5 MW) detected at Gaua volcano between 2000 and 2015 are ambiguous (Fig. 9a). Even though they occurred above the crater lake they appeared almost exclusively during the hot season (Fig. 9b) and were not associated to any reported activity. Hence, differently from Aoba volcano where independent observations validated the MIROVA dataset, we have not argument to support a genuine volcanic heat source for the rare (less than 2%), low and intermittent thermal anomalies detected at Gaua.

Conversely, the three thermal anomalies detected in early 2010, with radiant power higher than 5 MW, were related to a period of volcanic unrest that started in late 2009 (Global Volcanism Program, 2009; gray field in Fig. 9a). In fact, between September and December 2009 a new eruption started at Gaua volcano and was characterized by ash-bearing explosions and strong degassing from the summit of Mt. Garat. This activity was coupled with a marked discoloration of Letas Lake, as well as by the almost complete loss of green vegetation around the crater and in areas on the NW, W, and SW parts of the island (Global Volcanism Program, 2009). It is worth noting that this strong degassing activity, with ash and acid rain affecting food crops and contaminating the water, was not associated to any evident thermal anomaly detected by MIROVA.

However, on January 21st , 2010 (9 MW), March 28th, 2010 (24 MW) and April 6th, 2010 (14 MW), thermal activity become detectable by MIROVA (Fig. 8a) possibly due to stronger explosions than those previously described (Global Volcanism Program, 2009). The explosive activity in this period was slightly different from the previous one, with denser and darker plumes (more than 3 km high), thus suggesting the presence of major juvenile magma in the ash plumes (Global Volcanism

Program, 2009). A drop in both tremor and caustic effects on vegetation were recorded after mid-2010, although periodic explosions with ash and, more rarely, scoria bombs emissions continued until September, 2010 (Global Volcanism Program, 2010b). Ongoing degassing, and small-scale eruptions were reported during 2011 and 2013 but, according to the Global Volcanins Program (2013) the intensity of the activity was lower than during 2009-2010. The absence of clear thermal anomalies between 2011-2015 suggest that the thermal emissions associated to this weak explosive activity were very low and below the detection limit of MIROVA.

The Gaua's analysis put some constrain on the type of eruptive activity detectable by MIROVA. The elevated SO_2 levels and especially the heavy presence of ash in the volcanic plume, may have effectively prevented the detection of the most of the hotspots during 2009-2010 eruptive period. On the other hand, similar (or more powerful) explosive activity, emitting huge amount of SO2 and ash has also occurred at other volcanoes that however exhibited coeval thermal anomalies (see for example thermal anomalies detected during the 2013-14 explosive activity of Ubinas volcano; Coppola et al, 2015b). Hence, in our view the presence or absence of thermal anomalies associated to explosive activity is strongly dependent from the presence or proximity of "hot" magma to the surface. The fact that the only thermal anomalies of Gaua were detected during a later stage of the eruption, when major juvenile magma was present in the ash plumes support this hypothesis which however need further investigations.

Figure 9

6 - Conclusive remarks

In this paper we presented 15 years of satellite-based thermal observations at 5 Vanuatu's volcanoes. These data allowed us to show the large amount of information that can be retrieved from the analysis of MIROVA data over distinct volcanoes and covering a variety of volcanic activity.

In particular, we provided evidence of:

- Fluctuating magma column feeding the strombolian-vulcanian activity at Yasur volcano. At least seven cycles of stronger thermal activity has been recognized and possibly associated monthly-long degassing phases reported by Bani et al.(2009a). A very slow increasing trend seems also to characterize the activity between 2000-2015 and could be related to a gradual pressurization of the shallow magmatic system.
- Intermittent effusive and explosive activity at Lopevi between 2000 and 2007, followed by a 8 year-long period of quiescence. The effusive activity occurred along the northern and western flank of the volcano and produced high (> 100 MW) thermal anomalies; Three types of eruptions has been recognized on the basis of the recorded trends and durations; a low thermal regime has been also recognized and seems to characterize sporadic periods of mild strombolian activity within the summit crater.
- The first effusive eruption at Ambrym since 1989; this eruption lasted less than 48 hours (21-23 February 2015) and produced a lava flow with volume of 4.4 (± 2.2) Mm^3 with a minimum eruption rate of 27.3 (± 13.7) m^3 s^{-1}. The eruption took place within the summit caldera apparently from a fissure oriented radially from the Marum crater. The effusive trend display a fast waxing and waning effusive trend typical of pressurized basaltic system (Wadge 1981)
- A gradual but almost persistent increase of thermal output recorded at Benbow crater during the 2 years that preceeded the eruption. For the first time in 15 years the radiant power raised above 550 MW on January 17, 2015, about one month before the effusive eruption. This value could represent a critical pressurization state of Ambrym plumbing system that

may prelude an hazardous changes on the volcano activity (i.e lateral effusive activity, draining of the lava lake(s))

- Cyclic fluctuations of the Marum and Benbow lava lakes hosted at Ambrym volcano may last for months or years and interest one or both lava lakes. A rather empirical inference suggests that bulk thermal output of each lake is not simply related with the amount of sulfur emissions but rather with open- vs closed-system degassing processes;
- Cycles of major thermal activity within the Voui crater lake at Aoba volcano, including the occurrence of a main eruptive phase in December 2006, characterized by surtseyan activity. In addition to the prompt detection of high-temperature material ejected during phreatomagmatic and surtseyan activity (i.e. the sharp increase recorded between the 21 and the 25 of November 2005; Fig. 8) the results suggest that MIROVA system is also able to track long-term anomalous thermal activity related to the fluctuations of crater lake's temperature.
- Finally, the analysis of Gaua volcano provided an excellent test for evaluating the limits of MIROVA. In fact the volcano host a large crater lake on its summit (a challenging task for the algorithm due to the presence of temperature contrast on the summit of the volcano) and experienced a period of weak to mild explosive activity. The analysis reveals that less than 2% of false alerts are potentially triggered in this conditions and are always of low amplitude (i.e < 5 MW). On the other hand the analysis of Gaua volcano reveals that phreatic explosions, also if accompanied by huge sulfur degassing, may remain undetected by MIROVA since they not produce evident thermal signal detectable in the MIR region of the electromagnetic spectrum. We thus infer that the explosive activity (hereby regarded as producing volcanic plumes) may be detectable by MIROVA only if the hot magma-gas mixture is someway very close to the surface.

The obtained results support that the MIROVA system is a reliable tool for tracking thermal emissions related to different types of volcanic activity. These data may be integrated by field observations and other geochemical or geophysical datasets (i.e. sulfur emissions, deformations, seismicity, etc…) to have a more comprehensive picture in how a single volcano works. The advantage of this approach is that it provide detailed, complete and homogeneous datasets which are safely updated in near-real time (www.mirova.unito.it) and allows the detection of eruption onsets and unrest phenomena over a variety of volcanoes. We regard the application of this methodology as a key-factor in volcano monitoring that will improve our effort to mitigate volcanic risk

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Figure Captions

Figure 1 - (a) Simplified tectonic sketch map of Vanuatu archipelago. Selected thermal maps, provided by MIROVA, of the five analysed volcano are shown from (b) to (f). The thermal images (50 x 50 km) are centered on the summit of the volcano and draped over a shaded relief map.

Figure 2 – Timeseries of Volcanic Radiative Power (VRP), on logarithmic scale for (a) Yasur, (b) Lopevi, (c) Ambrym , (d) Aoba and (e) Gaua volcanoes. On the right panels, the frequency

distribution of log-transformed data (logVRP) is presented for each volcano. Note how each single volcano is characterized by a distinctive distribution.

Figure 3 – (a) VRP timeseries recorded over Yasur volcano between 2000 and 2015. At least seven cycles of more intense thermal activity have been recognized (gray field) and overlay a long-term increasing trend of about 0.8 MW per year (yellow dashed line). (b) Background Middle Infrared (MIR) radiance recorded over the summit area of Yasur (each point represent the most radiant non-alerted pixel) showing the seasonal thermal pattern. Note how the cycles of major thermal activity are unrelated to seasonal effects.

Figure 4 – (a) VRP timeseries recorded over Lopevi volcano between 2000 and 2015. The inset shown in (b) outlines a period of mild and intermittent explosive activity occurred between 2004 and 2005. Effusive periods are classified according to their dominant eruptive trend (gray field): (c) waxing-waning trend; *Type I*; (d) steady trend; *Type II*; (e) pulse-like trend; *Type IV* (see the text for more details).

Figure 5. (a) VRP timeseries recorded over Ambrym volcano between 2000 and 2015. Thermal output relative to the activity within Marum (b) and Benbow (c) craters reveals the occurrence of multiple monthly- to yearly-long cycles that modulate the level of the respective lava lakes. A clear increase in the thermal output was recorded since 2013 (prevalently due to the intensification of activity within Benbow crater) and anticipated the occurrence of the an intra-crater effusive eruption on February 21st, 2015 (the first sice 1989).

Figure 6. (a) to (e) A sequence of MODIS thermal maps showing the evolution of the thermal anomaly during the effusive activity of 21-23 February 2015. Note how the location of the hotspots clearly reveals the occurrence of effusive activity on the southern sector of the caldera. (b) The Time Averaged lava Discharge Rate (TADR) and cumulative erupted volume (retrieved by MODIS-derived VRP; eq. 2) suggest a fast waxing-waning effusive trend typical of pressurized eruptions. (c) Details of the southern portion of Ambrym caldera as imaged by Landsat 8 on March 21st, 2015 (Band combination 765). A new eruptive fissure is located above the main N 105 rift zone crater but seems to be oriented radially with respect to Marum cone at a distance of about 3 km. The newly emplaced flow field (red contours) is characterized by two 6-km-long lava flows covering a total area of about 2.2 km^2.

Figure 7 – (a) Cumulative radiant energy recorded at Marum (red) and Benbow (blue) craters between 2000 and 2015. As a whole the activity within the Marum crater constitute about 67% of the total thermal emissions of Ambrym. Note the sharp increase in thermal output of Benbow starting in 2014 that preceded the effusive eruption of February 21st 2015. Thermal activity at the two craters resumed almost immediately after the effusive event.

Figure 8 – VRP Timeseries (black stem) recorded at Aoba volcano between 2000 and 2015. Six main phases of activity (gray field labelled with roman numbers) are distinguished on the basis of the measured thermal anomalies. The red squares refers to the crater lake temperature anomaly estimated by Alain Bernard using ASTER images (modified from: http://www.ulb.ac.be/sciences/cvl/aoba/Ambae1.html).

Figure 9 – (a) VRP Timeseries (black stem) recorded at Gaua volcano between 2000 and 2015. All the detections below 5 MW seems to have been triggered during the warm season (as depicted from the Background Middle Infrared (MIR) radiance recorded over the summit area of Gaua (b)) and are considered false alerts. The three genuine volcanic hotspots detected on 2010 (> 5 MW) are associated to a period of unrest, characterized by huge degassing and ash-bearing volcanic explosions.