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EDITED BY

Yosuke Aoki,
The University of Tokyo, Japan

REVIEWED BY

Ryunosuke Kazahaya,
Geological Survey of Japan (AIST),
Japan
Gaetana Ganci,
Section of Catania, Italy

*CORRESPONDENCE

D. Coppola,
diego.coppola@unito.it

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Thermal unrest of a fumarolic field tracked using VIIRS imaging bands: The case of La fossa crater (Vulcano Island, Italy)

D. Coppola^{1,2*}, M. Laiolo^{1,2}, A. Campus¹ and F. Massimetti¹

¹Dipartimento di Scienze della Terra, Università degli Studi di Torino, Turin, Italy, ²Centro Interdipartimentale sui Rischi Naturali in Ambiente Montano e Collinare—NatRisk, Turin, Italy

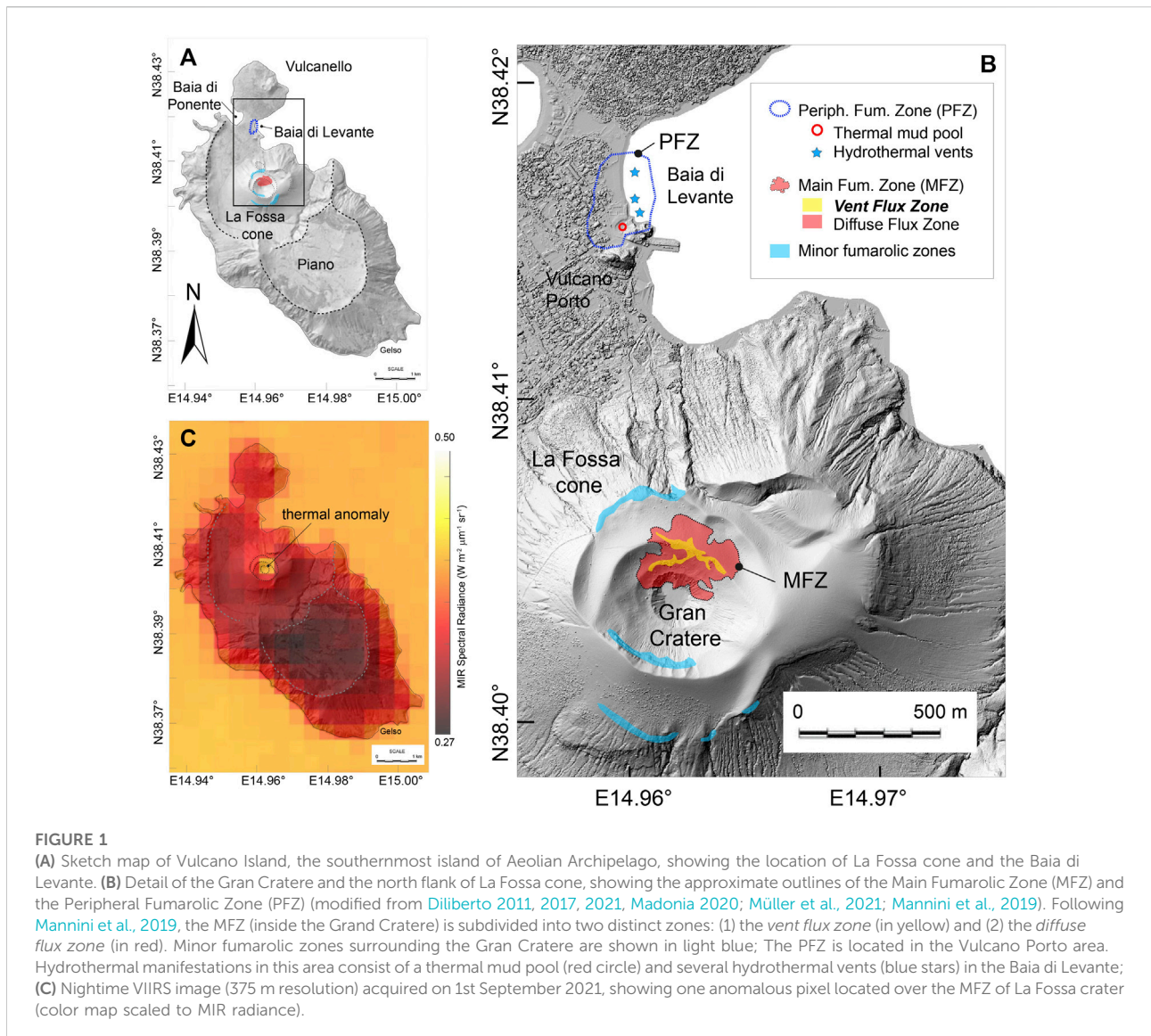
Detecting precursory signals before an eruption is one of the main objectives of applied volcanology. Among these signals, the variation of the emitted heat flux is certainly an important indicator of a state of disequilibrium within the magmatic system. Here we report the results of a detailed analysis of VIIRS (Visible Infrared Imaging Radiometer Suite) imaging bands (at 375 m spatial resolution) focused on measuring the Volcanic Radiative Power (VRP) emitted by the fumarole field of La Fossa crater (Vulcano Island, Italy) over the past decade (2012–2022). The analysis reveals that the long-term, steady-state VRP (baseline ~0.17 MW) was perturbed in 2020–2021 when a prolonged period of lower than normal ($<-2\sigma$) radiant flux preceded the major unrest phase that began in mid-September 2021. By early October the anomalous VRP had peaked at ~1.2 MW (6–8 times the baseline) then started to gradually decline in the following months. A subsequent thermal pulse was recorded in May–July 2022 and was accompanied by a period of seawater discoloration that affected the Baia di Levante (a shallow sea bay ~1.4 km north of La Fossa crater). The concomitance of these phenomena suggests the occurrence of a second pressurization phase driven by the arrival of deep magmatic fluids within both the central and distal degassing fumarolic zones. These results provide a complementary, important contribution to the understanding of the unrest of La Fossa crater and highlight the potential of VIIRS in detecting pre-eruptive signals at other poorly-monitored volcanoes characterized by high-temperature fumarolic activity.

KEYWORDS

volcanic unrest, la Fossa crater (vulcano island), satellite, thermal monitoring, VIIRS

Introduction

Together with ground monitoring networks (e.g., geochemistry, geophysics, geodesy), space-based thermal data are increasingly used for detecting volcanic unrest at quiescent volcanoes characterized by background fumarolic activity (Reath et al., 2016; Furtney et al., 2018; Ramsey et al., 2021). Thermal remote sensing offers an effective and safe tool to detect thermal anomalies and allows the heat flux to be measured safely and



homogeneously, now for decades ([Harris, 2013](#)). However, the ability to detect the fumarolic heat emissions from space strongly depends on the features of the thermal anomalies (i.e., number, size and temperature) as well as on the spatial, temporal, and spectral resolutions of the sensors used ([Harris, 2013](#)). Sensors like OLI (Operational Land Imager; onboard of Landsat 8) or ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), which use bands in the Thermal Infrared (TIR: 8–14 μm) with spatial resolutions of 90–100 m, have been proved to be well suited for mapping worldwide fumarole fields ([Vaughan et al., 2012](#); [Braddock et al., 2017](#); [Caputo et al., 2019](#); [Reath et al., 2019](#); [Silvestri et al., 2019](#); [Ramsey and Flynn 2020](#); [Way et al., 2022](#)) as well as for quantifying the long-term thermal flux at La Fossa volcano (Italy; [Harris and Stevenson 1997a, b](#); [Mannini et al., 2019](#)). However, their

temporal resolution (1 image every 10–16 days approximately), together with the cloud coverage issues (about 55% of ASTER nighttime images are covered by clouds over Vulcano Island) make their use still limited for near-real-time monitoring purposes (e.g., [Wadge & Aspinall, 2014](#); [Wadge et al., 2014](#); [Mothes et al., 2017](#)).

On the other hand, moderate-temporal and-spatial resolution sensors like AVHRR (Advanced Very High Resolution Radiometer), MODIS (Moderate Resolution Imaging Spectroradiometer) or VIIRS (Visible Infrared Imaging Radiometer Suite), offer an image frequency suitable for daily monitoring of global volcanic (magmatic) activity by providing up to four images per day ([Coppola et al., 2020](#)). Some pioneering studies ([Harris and Stevenson 1997a,b](#)) have demonstrated the ability of AVHRR to detect thermal anomalies associated with degassing of La Fossa

volcano, but their quantification remained difficult because of the coarse resolution of these sensors (about 1 km). As a result, there is currently no operative, satellite hot-spot detection system capable of automatic daily monitoring of a fumarole field.

In this work, we show that the data provided by the VIIRS Imaging Bands (375 m resolution in the middle infrared; MIR: 3–5 μm) can bridge this gap, and allow for monitoring radiant flux of La Fossa crater fumarolic areas (Vulcano Island, Italy) from space. In particular, we demonstrate for the first time how these data can automatically track and follow the background thermal activity of this volcano, and allow the timely detection of the anomalous heat flux that characterize the ongoing unrest, started in September 2021.

The island of Vulcano is the southernmost of the Aeolian islands (Figure 1) and in historical times it has been characterized by frequent eruptions of moderate size (Frazzetta et al., 1983; De Astis et al., 2013; Di Traglia et al., 2013). The last eruptive period dates back to 1873 AD when explosive events, separated by periods of intense degassing, occurred at La Fossa cone, the most recent eruptive center of the volcano (Figure 1). This activity culminated with the 1888–1890 AD eruption when La Fossa was the site of a violent explosive activity, currently known as the archetypal “Vulcanian eruption” (Mercalli 1907). Since then, fumarolic activity has been established on the summit crater, called Gran Cratere (Figure 1B), with gas emissions reaching temperatures up to $>500^\circ\text{C}$ (Diliberto 2017, 2021). Between 1987 and 1993 an unrest episode was characterized by an increase in fumarolic activity accompanied by significant variations in CO_2 flux in the crater area and the peripheral systems at the base of the cone (Barberi et al., 1991; Chiodini et al., 1996; Montalto 1996). The unrest included the occurrence of shallow volcano-seismic crisis, which however did not culminate in an eruption (Barberi et al., 1991). The seismic sequences was interpreted as the result of an increasing magmatic component of the hydrothermal fluids causing pressurization of the hydrothermal system located 0.5–1.5 km below La Fossa crater (Alparone et al., 2010). Other minor unrest phases were also recorded in 2004–2005, 2009, and 2017 (Granieri et al., 2006; Paonita et al., 2013; Ricci et al., 2015; Selva et al., 2020), but were characterized by weak or not significant intensifications in superficial micro-seismicity and likely involved a modest increase in the total contribution of magmatic fluids to the volcanic system (Aiuppa et al., 2005; Selva et al., 2020). A polybaric system, with several magmatic ponding zones, is supposed to exist under Vulcano, with the shallowest storage zone located at 1–2 km beneath La Fossa cone (Selva et al., 2020 and references therein). Above this zone a very shallow hydrothermal system feeds the main fumarole field located in the crater area, while a second area of exhalations is located in the “Baia di Levante”, located ~ 1.4 km north of the crater (Chiodini et al., 1995; Figure 1B).

A new major episode of unrest began in September 2021 (INGV weekly reports, 2021) and was followed on 1 October

2021 by the raising of the alert level from green to yellow (Dipartimento della Protezione Civile, 2021). The unrest (still ongoing at the time of this writing) is characterized by an increase in degassing, by variations in the temperature and chemical composition of the fumaroles (Inguaggiato et al., 2022), as well as by the appearance of micro-seismicity associated with movement of fluids (very long period events) accompanied by a moderate deformation of La Fossa cone (INGV weekly reports, 2021, 2022a, b).

Heat flux at La Fossa volcano

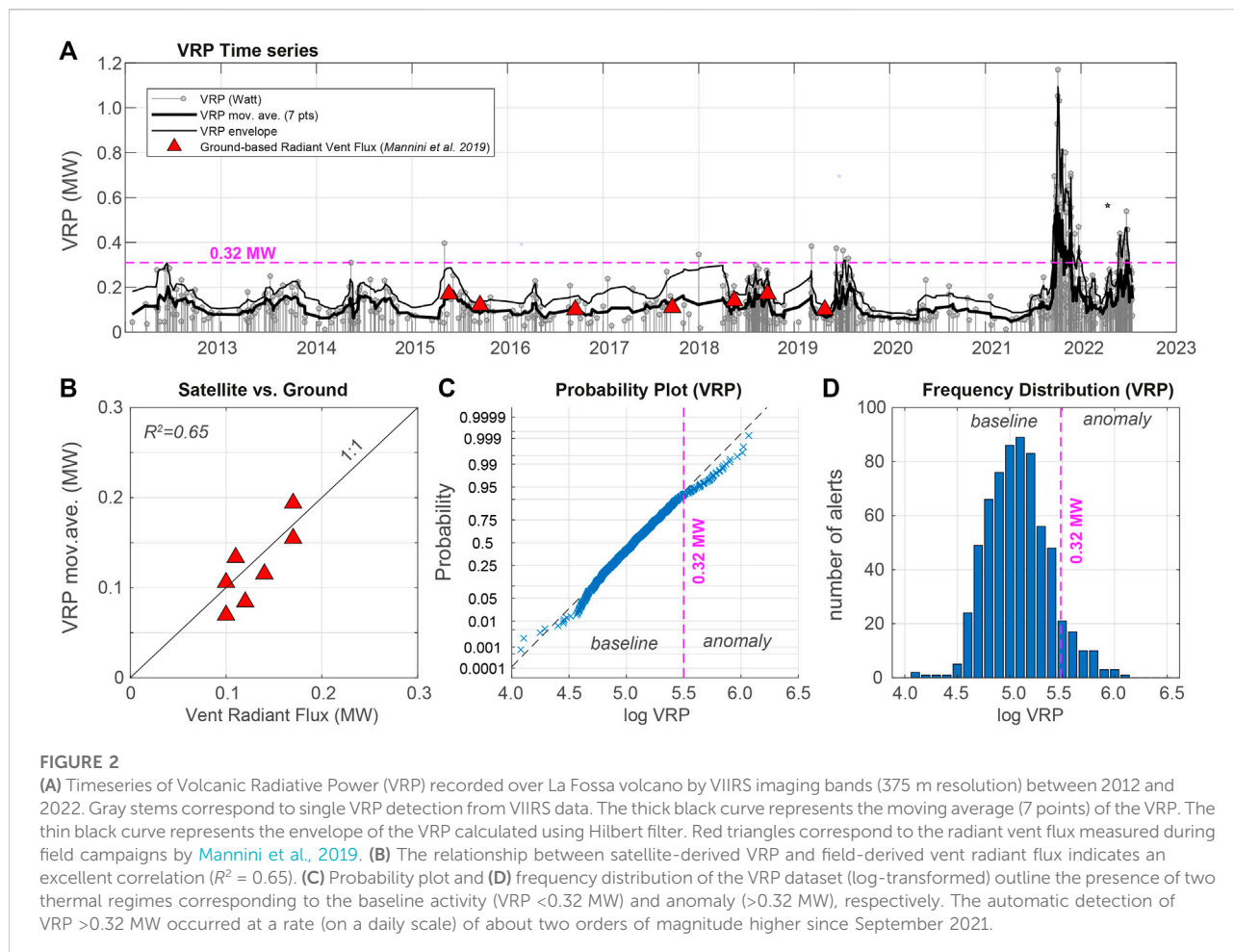
Heat release at La Fossa is monitored since 1984 by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) through a network of permanent ground stations located in the Main Fumarolic Zone (MFZ), in the Peripheral Fumarolic Zone (PFZ), and in minor steam-heated soil zones around the cone (Diliberto 2011, 2017, 2021; Madonia 2020; Figure 1B).

The MFZ is an area of persistent degassing located on the northern edge of the Gran Cratere (Figure 1B). According to Mannini et al., 2019, the MFZ is composed of two distinct thermal regions (Figure 1B) (I) a broad zone of diffuse surface degassing, named the *diffuse flux zone*, and characterized by ground temperatures a few degrees above the background and (II) a zone of focused fumarolic venting, named *vent flux zone*, where a large number of open vents and fractures (fumaroles) are distributed across the field. The fumaroles have temperature ranging from less than 100°C to more than 500°C and result from the mixing between magmatic and hydrothermal fluids (Chiodini et al., 1995; Harris and Maciejewski 2000; Diliberto 2011; Madonia 2020).

A series of minor fumarolic areas are also present on the external rims of the La Fossa cone (Figure 1B). These exhalating zones are composed of low-temperature fumaroles (typically $<100^\circ\text{C}$) that have a geochemical signature compatible with a variable mixing between hydrothermal and shallow meteoric components (Madonia 2020).

Finally, the peripheral fumarolic zone (PFZ) is located ~ 1.4 km north of La Fossa crater, in an area that includes the village of Vulcano Porto, the Baia di Levante beach, and the shallow sea areas in front of it (Figure 1B). In this zone, famous for the thermal mud pool, the presence of an extensive hydrothermal aquifer is testified by diffuse degassing of CO_2 together with numerous carbon-rich thermal wells (up to 80°C) and several bubbling hydrothermal vents ($<100^\circ\text{C}$) (Federico et al., 2010; Diliberto et al., 2021).

The region of greatest heat loss is certainly the MFZ, which in 1998 produced about $\sim 90\%$ of the total heat flux of La Fossa volcano (Chiodini et al., 2005). However, it is well known that the number and extent of the fumaroles vary with time in response to fumarole migration, self-sealing, or because of variation in the deep heat source (Harris and Maciejewski 2000; Harris et al.,



2009; Harris et al., 2012; Mannini et al., 2019). For example, between 1994 and 1997 Harris and Maciejewski 2000, measured an enlargement of the exhalation area which brought the heat flux released by the MFZ to increase from 45 to 67 MW. On the other hand, using satellite and field data acquired between 2000 and 2019, Mannini and coauthors (2019), calculated a total heat flux from the MFZ ranging from 5 to 14 MW (much lower than in the 90s), compatible with a general reduction of the number, distribution, and extension of the fumarolic areas.

For the same period Mannini et al. (2019) estimated that most of the heat released from the MFZ is lost through convection (~85%), while the remaining 15% (i.e., from 0.68 to 1.92 MW) represents the radiative component. The latter is in turn composed of the contribution of the two thermal zones described above; that is, 0.58–1.75 MW are radiated from the *diffuse flux zone* and only 0.1–0.26 MW are radiated from the *vent flux zone*. These partitionings suggest that the heat flux radiated by the vent flux zone alone, although composed of the highest temperature fumaroles, represents only 1–2% of the total heat flux. On the

other hand, the same authors found a strong coupling between the heat flux radiated by the two zones of MFZ, so that the perturbations of the hydrothermal system caused by deep sources manifest themselves through variations of heat flux from both regions of MFZ.

Methods

Visible Infrared Imaging Radiometer Suite is a whiskbroom multispectral sensor that acquires data in 22 spectral bands (from 0.4 to 12.5 μm). Among these two Imaging Bands (named I04 and I05), at 375 m resolution, acquire in the Middle Infrared (MIR) and Thermal Infrared (TIR) regions (at 3.74 and 11.45 μm , respectively). Currently, two VIIRS sensors are mounted onboard the NASA and NOAA's Suomi-NPP (in orbit from October 2011) and JPSS-1 (or NOAA-20, in orbit from November 2017) satellites (Cao et al., 2017). In this work, we have elaborated 7,723 nighttime images acquired above La Fossa volcano between 19 January 2012 and 15 July 2022 (Figure 2). The data have been elaborated by applying

the MIROVA algorithm to the VIIRS Imaging Bands, following the procedure already used for MODIS (Coppola et al., 2015) and VIIRS (Campus et al., 2022) bands, at 1 km and 750 m resolution, respectively. Thanks to the improved spatial resolution of the Imaging Bands, the algorithm allowed to detect thermal anomalies over La Fossa volcano (as the one shown in Figure 1C), otherwise undetected using MODIS (1 km) and VIIRS (750 m). Hence, for each hot-spot contaminated pixel we calculated the Volcanic Radiative Power (VRP) using the MIR-method (Coppola et al., 2013):

$$VRP = A_{pix} k_{MIR} \Delta L_{MIR} \quad (1)$$

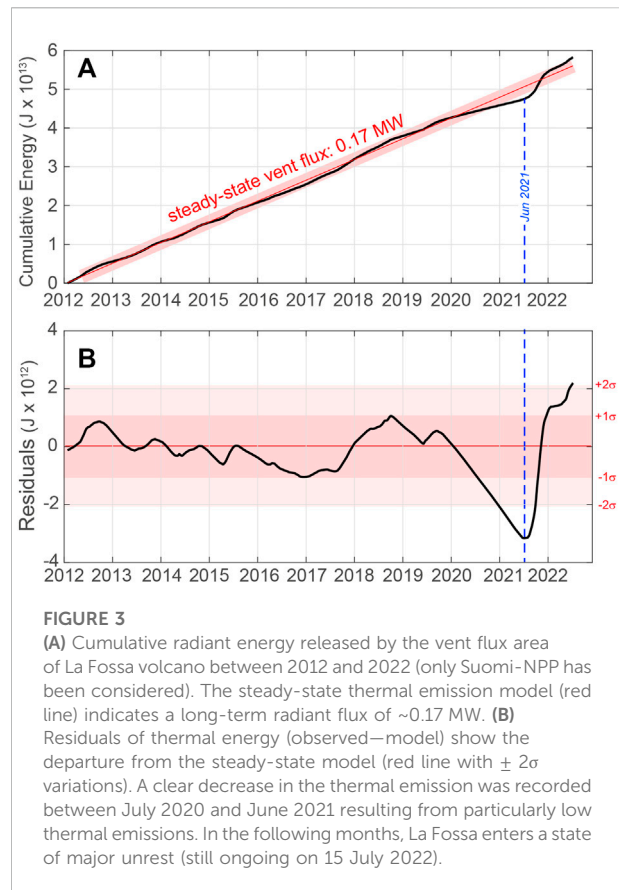
where A_{pix} is the pixel size (140625 m² for VIIRS Imaging Bands), ΔL_{MIR} is the excess of MIR radiance (difference between the radiance of the hot-spot contaminated pixel and the background) and k_{MIR} is a wavelength-dependent constant. The approach is inherited from the more common Fire Radiative Power and is based on the quasi-linear relationship between the MIR spectral radiance (in W m⁻² μm⁻¹ sr⁻¹) and radiant flux density (in W m⁻²), existing for temperatures between 600 and 1500 K (Wooster, 2003). This proportionality is expressed by the constant k_{MIR} which, in the case of I04 band, centered at 3.74 μm, has a value equal to ~7.16 μm sr (for details on how to calculate the constant see Wooster, 2003).

For volcanic thermal features with temperatures comprised in the range where the approximation holds, the MIR-method allows estimating the VRP with an error of 30% (Coppola et al., 2013). On the other hand, for features composed of thermal components even lower than 600 K, the VRP underestimates the total flux thus representing only the fraction radiated by a smaller and hotter portion of the feature (Coppola et al., 2013). As it will be shown below, in the specific case of the La Fossa volcano, the VRP proved to be very efficient in measuring the heat radiated exclusively by the *vent flux zone* of the MFZ.

More specific approaches can be applied to estimate the total heat flux of the MFZ (this including both the vent and diffuse flux zones), by assuming for example the size/temperature of each region, their emissivities, as well as the transmissivity of the atmosphere (Harris and Stevenson, 1997a). However, in this work, we preferred to use the VRP “as is”, since it is immediately applicable in near-real-time, without any atmospheric correction nor the need for any assumptions (which could be nontrivial during ongoing eruptive crises). Moreover, measuring the VRP of La Fossa’s fumaroles allows a direct comparison with the radiant power continuously measured on other volcanic systems (for example Stromboli) and by automatic systems such as MIROVA, MODVOLC, and FIRMS.

Results

The timeseries of VRP recorded between 2012 and 2022 is shown in Figure 2A, where is combined with the periodic measurements of the heat radiated by the *vent flux zone*, as



derived from ground thermal images (Mannini et al., 2019). As a whole between 28 January 2012 and 15 July 2022, VIIRS-375 detected 696 anomalies with VRP ranging from ~0.01 to ~1.17 MW.

The comparison between the satellite data (moving average on seven points) and punctual ground measurements (Figure 2B) reveals a fair correlation ($R^2 = 0.65$), with points dispersed around the 1:1 ratio. This relationship, although purely empirical, suggests that in the case of La Fossa, the VRP retrieved using the MIR-method (Eq. (1)) can be considered a reliable proxy of the heat radiated by the *vent flux zone*.

During typical fumarolic activity (e.g. between January 2012 and August 2021) the VRP fluctuates well below 1 MW (Figure 2D), with a mean value of ~0.12 MW and a standard deviation (σ) of ~0.06 MW. In this period, VIIRS 375 detected 426 anomalies with an average interval between detections of ~9 days. This low detection rate and the low VRP explains the lack of thermal anomalies at La Fossa volcano detected by the most common automatic systems such as MIROVA (<https://www.mirovaweb.it/>), MODVOLC (<http://modis.higp.hawaii.edu/>) or FIRMS (https://firms.modaps.eosdis.nasa.gov/active_fire/), whose detection limit is about 1 MW (Coppola et al., 2020).

On the other hand, the frequency distribution (log-transformed) and the probability plot of the whole VRP dataset (Figures 1C,D) show a pattern composed of two thermal regimes (hereby called baseline

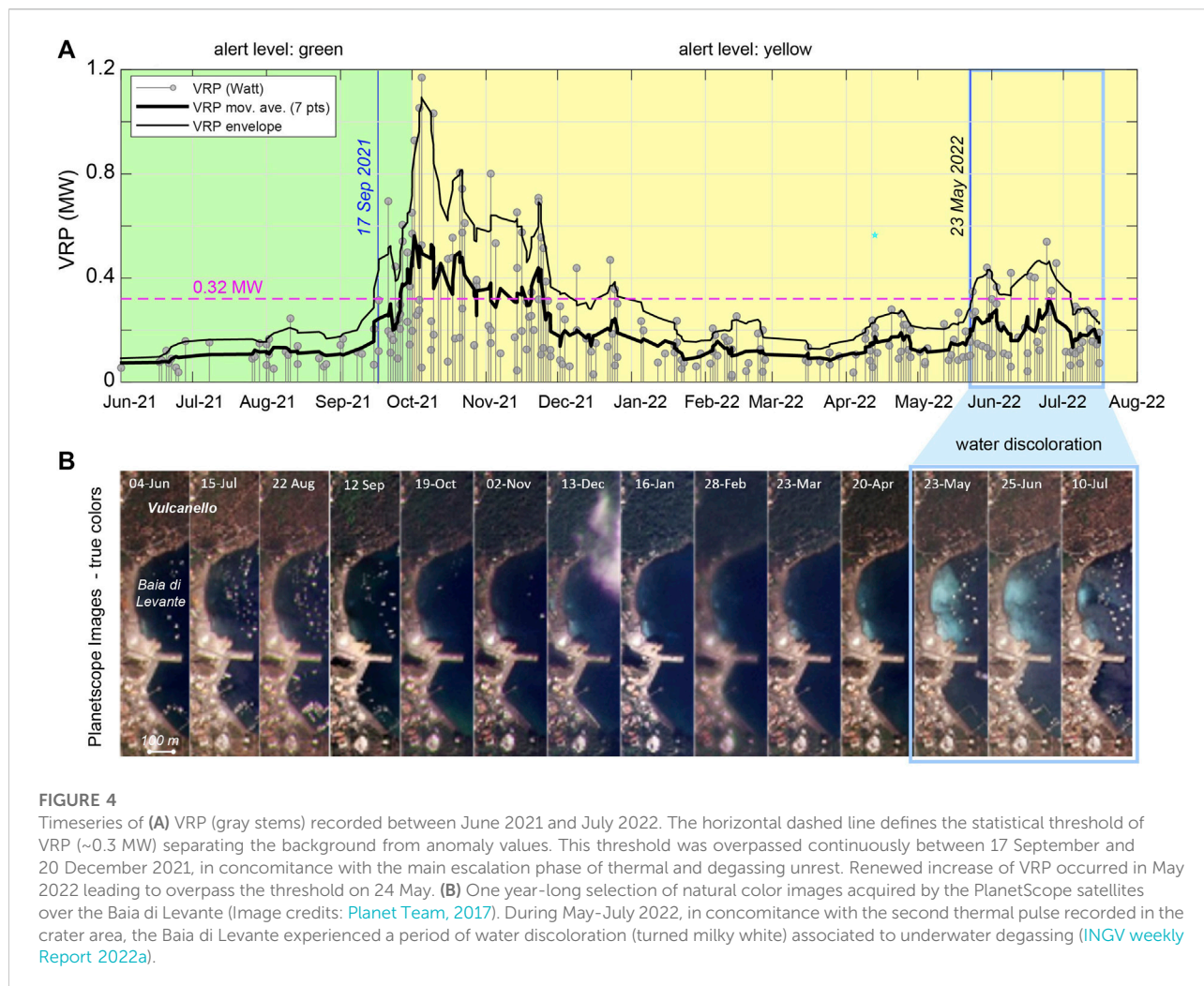


FIGURE 4

Timeseries of **(A)** VRP (gray stems) recorded between June 2021 and July 2022. The horizontal dashed line defines the statistical threshold of VRP (~ 0.32 MW) separating the background from anomaly values. This threshold was overpassed continuously between 17 September and 20 December 2021, in concomitance with the main escalation phase of thermal and degassing unrest. Renewed increase of VRP occurred in May 2022 leading to overpass the threshold on 24 May. **(B)** One year-long selection of natural color images acquired by the PlanetScope satellites over the Baia di Levante (Image credits: Planet Team, 2017). During May–July 2022, in concomitance with the second thermal pulse recorded in the crater area, the Baia di Levante experienced a period of water discoloration (turned milky white) associated to underwater degassing (INGV weekly Report 2022a).

and anomaly) separated at VRP equal to ~ 0.32 MW ($\log_{10} \text{VRP} = 5.5$). Numerous detections above the 0.32 MW threshold were recorded after September 2021, coinciding with the unrest phase.

Discussion

The decadal trend of VRP delineates overall stability in VRP (steady-state activity in Harris and Stevenson, 1997b) which fluctuated mostly between 0.1 and 0.2 MW (Figure 2A). Two periods of increased thermal activity, occurred in the summer of 2018 and 2019 when frequent alerts (every 1–2 days), were punctuated by some measurements above 0.3 MW. These anomalous heat releases were accompanied by increased in-soil CO_2 flux measured at different sites, including the PFZ (Di Martino et al., 2020). Based on $\delta^{13}\text{C}-\text{CO}_2$ and CO_2 flux data, Di Martino et al., 2020, suggest that such increases reflected an increase of degassing from a deep magma body, therefore tracked also by the increase in VRP.

On the contrary, from 2019 to the first half of 2021, the venting area was characterized by a prolonged period of lower than normal VRP (~ 0.1 MW), as evidenced by the cumulative curve of thermal energy release (Figure 3). Indeed, in that period there is a deviation from the long-term steady-state thermal trend (~ 0.17 MW), which reaches a minimum in June 2021 clearly outside the normal fluctuations ($\pm 2\sigma$) recorded since 2012 (Figure 3B). Changes in heat flux associated to fumarole migration and sealing were already observed between 1994 and 1999 (Harris and Maciejewski 2000). According to Harris and Maciejewski 2000, a decrease in the heat flux of MVZ could be ascribed to 1) a decrease in system permeability (including shallow or deep sealing) and/or 2) a decrease in degassing of the deep, magmatic source. We do not have sufficient data to be able to distinguish between these two mechanisms but it is interesting to note that precursory decreases in the gas/heat flux before explosive eruptions are reported elsewhere (with a variable duration of decreased periods spanning from years to minutes) and commonly attributed to the sealing and pressurization of the

hydrothermal system (Christenson et al., 2010; Yokoo et al., 2013; Kazahaya et al., 2016, 2019; Mori et al., 2017).

Starting from June–July 2021, a reversal trend is observed in the VRP timeseries, with a thermal flux that gradually returns to increase (Figure 4A). This change was roughly concomitant with an increase in CO₂ flux in the crater area followed, in August, by an increase in the temperature of the fumaroles, and by a slight increase in temperature and conductivity in some wells around cone (INGV report 2021). The unrest becomes evident in mid-September when a net increase in magmatic gas flux was recorded in the crater area and in the thermal aquifer at the base of the cone (INGV report 2021). Since 13 September 2021 the clinometric network of INGV has recorded a slight uplift of the cone, accompanied by an increase in the frequency of occurrence of seismic events, which include (for the first time at this volcano) Very Long Period (VLP) events (INGV report 2021). This acceleration has been recorded by VIIRS (Figure 4A), which, starting from 17 September, begins to detect frequent thermal anomalies with VRP values higher than the statistical threshold (0.32 MW).

The escalating signs of volcanic unrest led the Civil Protection Department (DPC) to switch from the green alert level (the volcano is in a state of quiescence) to the yellow one (state of minor superficial hydrothermal crisis of the volcano) on October 1st (Dipartimento della Protezione Civile, 2021).

A few days later, on 5 October, the VRP reached a peak of ~1.17 MW (Figure 4A), after which a slight decrease started to be observed, in agreement with a gradual reduction of the seismicity, deformation, and CO₂ fluxes in soils (INGV report 2021). Between February and April 2022 the VRP decreased to values just above the baseline, albeit with a frequency of ~0.7 alerts/day, which is about 7 times higher than the typical detection rate during the baseline activity.

A new increase in VRP begins to be recorded in April 2022 (Figure 4A) and was followed, on 22–23 May, by an anomalous degassing event from underwater hydrothermal vents in the Baia di Levante (INGV report 2022a; Figure 4B). This event caused the discoloration of the seawater, clearly visible on the PlanetScope images (Planet Team, 2017) acquired on 23 May (Figure 4B). This second thermal pulse reached the peak on 24 June (~0.54 MW) and then decreased in the first weeks of July. At the time of this writing (15 July) frequent thermal anomalies are still detected with VRP decreasing below 0.3 MW; the discoloration of the water in the Baia di Levante is still present albeit in a smaller area (Figure 4B). Notably, this latter monthly-long thermal pulse and the peripheral submarine degassing event were also accompanied by the resumption of local seismic activity, likely linked to the dynamics of hydrothermal fluids (INGV weekly Report 2022b).

During the 1988–90 crisis anomalous temperature and degassing occurred also outside the crater area, including the Vulcano Porto area (Capasso et al., 1999). A link between central (MFZ) and peripheral (PFZ) heat flux has been also proposed by Chiodini et al. (1991) who found a positive correlation between increased inputs of high-

temperature fluids at the crater and increases in temperature and pressure estimated for Baia di Levante fluids. If this model also applies to the current unrest phase, the pulsation observed in May–July 2022 could effectively represent a second pressurization phase with deep fluids affecting both the MFZ and PFZ.

Conclusive remarks and perspective

The unrest of La Fossa continues as this work is elaborated and further, more in-depth analysis will be possible by integrating satellite data with multiparametric measurements carried out on the ground (e.g., Diliberto et al., 2022). These preliminary results demonstrate the effectiveness of VIIRS 375 m data in tracking and quantifying the baseline thermal activity of the La Fossa volcano and promptly detecting any variation from the steady-state conditions, associated with volcanic unrest. These findings are of particular value, especially for remote and poorly-monitored volcanoes, where the satellite data may be the only source of information capable of detecting pre-eruptive signals (Furtney et al., 2018). The current satellite thermal monitoring systems (e.g., MIROVA, MODVOLC) are based on MODIS data whose detection limit (~1 MW) allows monitoring active volcanoes and tracking ongoing eruptions (Coppola et al., 2020). The use of VIIRS imaging bands, at 375 m resolution, offers new opportunities for monitoring of quiescent volcanoes, as it lowers the detection limit by more than an order of magnitude and enables the detection of smaller and colder anomalies associated with fumarolic fields. We thus suggest that the systematic use of these data on a global scale may contribute to the timely detection and characterization of further unrest worldwide.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CD conceived and wrote the work. CA adapted the MIROVA algorithm to VIIRS data. CD, LM, CA, and MF contributed to develop, maintain and analyzed the MIROVA data in NRT. All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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