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Search for anomalies in Stromboli's pre-paroxysm activity through an automatic hybrid method of time series analysis

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Abstract

Stromboli (Italy) is an open-vent volcano with persistent explosive activity producing up to five hundred mild explosions per day. Fluctuations in explosion intensity, varying even by orders of magnitude in terms of emitted volume and their subsequent impact on the surrounding regions, sometimes occur abruptly. Consequently, identifying precursors of larger eruptive activities, particularly for more intense (paroxysmal) explosions, is challenging. In order to search for anomalies in the pre-paroxysm activity related to the summer 2019 eruption, we applied a hybrid method to the automatic analysis of geophysical and geochemical time series. This approach is based on the combination of two methods: 1. the Empirical Mode Decomposition (EMD) and 2. the Support Vector Regression (SVR). The aggregation of these two methods allowed us to identify anomalies in the patterns of the geophysical and geochemical parameters measured on Stromboli in a ten-month period including the July-August 2019 eruption. The results of this study are encouraging for an improvement of the monitoring systems and for volcano early warning applications.

Keywords: Stromboli volcano, Volcanic monitoring, data analysis, multiparametric geophysics, paroxysmal explosions

1. Introduction

Identifying the precursors of intensity changes within low and medium intensity activity styles is of paramount importance to ascertain the activity state of open vent volcanoes, particularly those exhibiting persistent activity. It also plays a critical role in determining alert levels, thus enabling the establishment of an effective early warning system. To achieve this, integrated multi-parameter monitoring systems with real-time data transfer are crucial. However, as these systems become more complex over time, there is a growing need for increasingly robust and potentially automated methods to identify anomalies in time series, especially when the expected parameter variations are small and potentially very rapid. At Stromboli, the system for assessing the volcano's activity status and determining the appropriate alert levels relies on scenarios of a gradual escalation in eruptive activity, which serves as a precursor to the transition from explosive to effusive activity. This approach is based on the observation that the most hazardous phenomena, both for Stromboli itself and the surrounding regions, such as tsunamis triggered by landslides of the Sciara del Fuoco, as happened in 2002, are associated with eruptive events related to the shift from explosive to effusive activity (e.g. Di Traglia et al., 2014; 2023a,b). This behavior of Stromboli volcano was also observed during the 2007 (Casagli et al., 2009; Calvari et al., 2010) and 2014 (Di Traglia et al., 2018) eruptions. However, the 2019 eruption revealed the limitations of this approach. Stromboli's activity was marked by highly explosive events, which significantly impacted the island (Turchi et al., 2020, 2022), and that had the potential to generate tsunamis triggered by landslides or column-collapse pyroclastic density currents (PDCs; Giordano and De Astis 2021). In this case, monitoring persistently active volcanoes requires additional approaches. For this topic, Stromboli is a good case study thanks to its persistent activity and its easily reachable location (Fig. 1). It is characterized by typical Strombolian activity (Fig. 2), which consists of several hundred small explosions per day (Barberi et al., 1993; Chouet et al., 2003; Calvari et al., 2012; Bevilacqua et al., 2020; Calvari et al., 2021; Calvari et al, 2022). Most of the erupted products fall on the upper slope of the Sciara del Fuoco, which is subject to frequent landslides due to the considerable steepness and the loose pyroclastic material that is deposited on it (Bonaccorso et al., 2003; Falsaperla et al., 2008; Esposito et al., 2013; Di Traglia et al., 2023a). The Strombolian activity originates from several eruptive vents located on the summit of the volcano, mainly grouped in three areas: north–east (NE); central (C) and south–west (SW) (Tioukov et al., 2019; 2022).

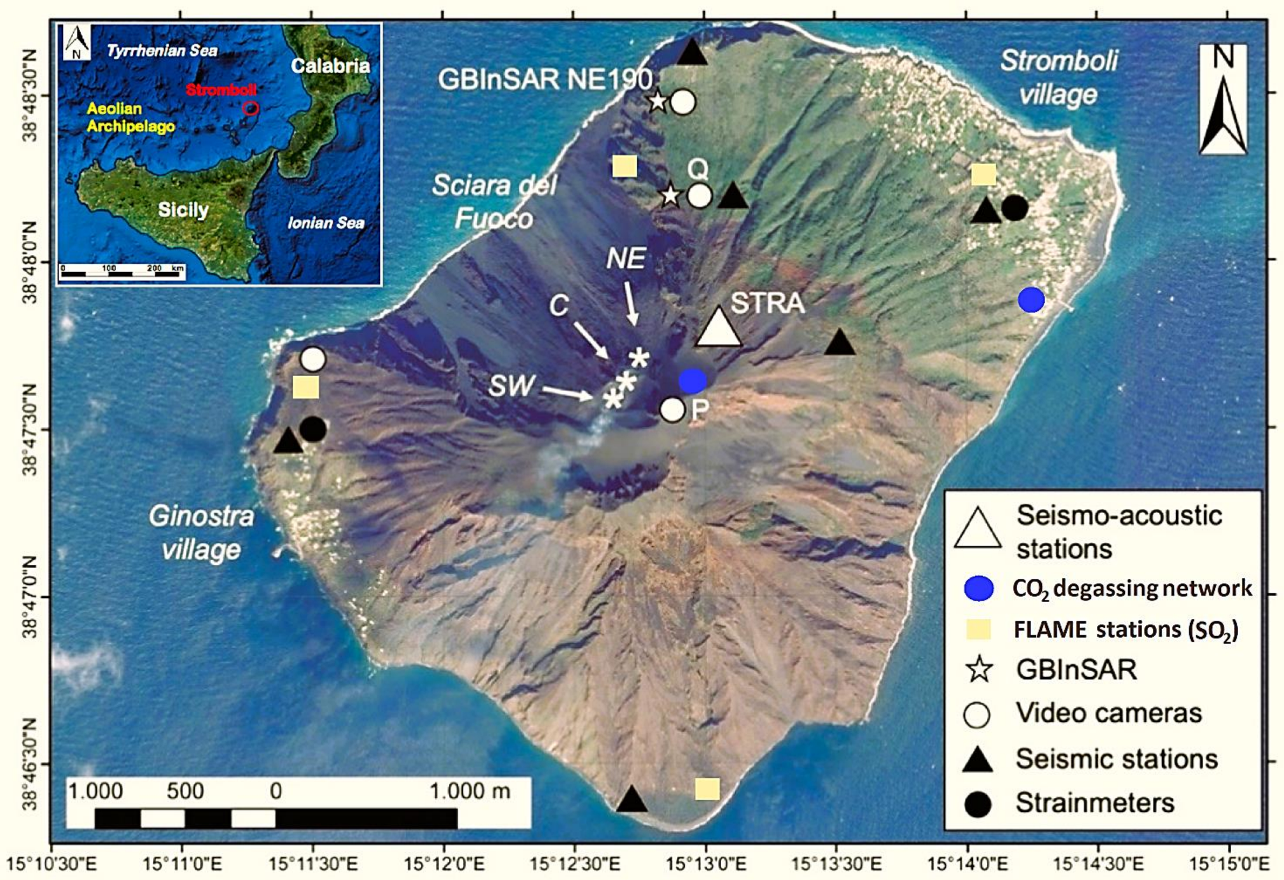

Figure 1. Map of Stromboli Island (Italy) with the location of the INGV (Istituto Nazionale di Geofisica e Vulcanologia) and UniFi (University of Florence) monitoring stations: the black circles are the strainmeters; the black triangles are the seismic stations; the white circles indicate the position of the video cameras; the white stars are the GBInSAR devices; the yellow squares are the locations of the FLAME network stations; the blue circles are the stations of the soil CO_2 degassing geochemical network; the white triangle is the STRA seismic–acoustic station; the white asterisks are the main vent regions, with the white arrows indicating the SW, C and NE crater zones. P indicates the Pizzo Sopra la Fossa view site. The inset on the upper left displays the position of Stromboli island (red circle) in the southern Tyrrhenian Sea.

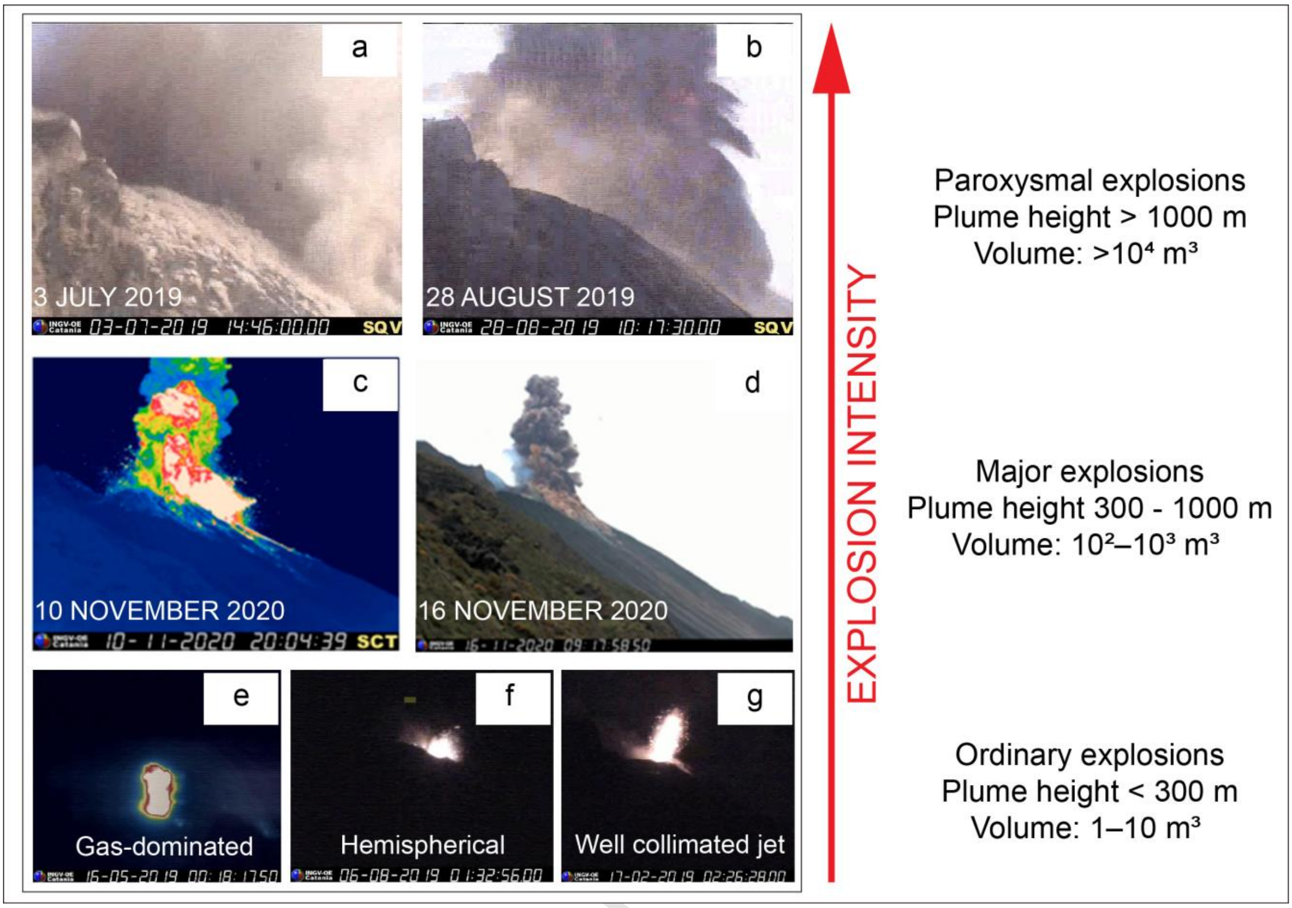

Figure 2. Schematic representation of the explosive activity of Stromboli (modified after Calvari et al., 2021; Giudicepietro et al., 2022; Voloschina et al., 2023). a: eruptive column of the 3 July 2019 paroxysmal explosive event imaged by the SQV visible camera located on the east flank of the Sciara del Fuoco (SdF); vertical Field of View (FOV) is ~ 500 m. b: eruptive column of the 28 August 2019 paroxysmal explosive event imaged by the SQV visible camera located on the east flank of the SdF. c: thermal image from the SCT camera located at the northern edge of the SdF showing the eruptive column of the 10 November 2020 major explosion; vertical field of view ~ 300 m. d: eruptive column from the SCV visible camera located at the northern edge of the SdF of the 16 November 2020 major explosion; vertical FOV is ~ 600 m. e: thermal image from the SPT camera located at Il Pizzo (P, Fig. 1) showing from south-east a gas-dominated explosion; vertical FOV is ~ 300 m. f, g: side view of the hemispherical and well–collimated jet from the ordinary explosions imaged from the SQV visible camera.

After the end of the 2014 effusive eruption a period of low activity occurred, which ended in the spring 2017, when more energetic ordinary explosive activity and major explosions resumed (Giudicepietro et al., 2019). Studies over the last 20 years have shown that the lava flows due to the opening of eruptive fissures on the slope of the volcano such as those of 2003 (Calvari et al., 2005), 2007 (Martini et al. 2007; Giudicepietro et al., 2009, Calvari et al., 2010) and 2014 (Rizzo et al., 2015; Di Traglia et al., 2018) were preceded by changes in seismic, deformation, and geochemical parameters (Martini et al. 2007; Giudicepietro et al., 2009; Marchetti et al., 2009; Laiolo et al., 2016; Giudicepietro et al., 2023). Variations in these parameters, such as the increase in the hourly rate of Very Long Period (VLP) events, the seismic amplitude, e.g. RSAM (Martini et al., 2007; Giudicepietro et al., 2009; Calvari et al., 2020; Giudicepietro et al., 2020), the soil CO_2 flux (Laiolo et al., 2016; Inguaggiato et al., 2020), can be precursors of effusive eruptions.

On the other hand, variations of the parameters routinely monitored were not recorded before the occurrence of anomalously large explosive eruptions, i.e. expected precursory signals were not observed in the data, such as the paroxysms occurred on 2003 (D'Auria et al., 2006), 2007 (Bonaccorso et al., 2012; Martini et al., 2007) and 2019 (Andronico et al., 2021; Ripepe et al., 2021; Viccaro, et al., 2021). In fact, these eruptions occurred suddenly, and in particular the 2003 and 2007 paroxysms occurred unexpectedly during major effusive phases, whereas the 3 July 2019 paroxysm occurred in a period in which Stromboli's activity was considered normal, and was anticipated by a few minutes of ground deformation (Giudicepietro et al., 2020; Ripepe et al., 2021).

In this work we consider the period from 15 November 2018 to 15 September 2019. The eruptive activity of this period was characterized by a small overflow from the NE vent that occurred on 6 December 2018, when the intensity of the persistent Strombolian activity was high. A major explosion occurred on 25 June 2019, which shortly preceded and heralded the 3 July paroxysm (Calvari et al., 2021; Corradino et al., 2021; Giudicepietro et al., 2022). The 3 July paroxysm was also preceded by a small lava flow output within the crater area that occurred a few seconds before the main blast (Andronico et al., 2021; Calvari et al., 2021). This phase was preceded by ground deformations recorded by tiltmeters, dilatometers and GBInSAR (Di Lieto et al., 2020; Giudicepietro et al., 2020; Di Traglia et al., 2021; Ripepe et al., 2021). The paroxysmal explosion was followed by an effusive flank eruption that lasted until the end of August 2019 (Calvari et al., 2021), with the emplacement of $\approx 2.3 \times 10^6$ m^3 lava flow field (Di Traglia et al., 2022). While lava flow output was still going on, on 28 August 2019 another paroxysmal explosion occurred at the summit, displaying the same sequence of events of the 3 July. It started with a blast that destroyed the crater terrace, and formed an eruptive column rising a few kilometers above the craters. The column collapsed on the Sciara del Fuoco forming two pyroclastic density currents (PDCs) spreading on the sea surface out to an estimated distance of 2 km from the coast (Calvari et al., 2021; Giordano and De Astis, 2021). This triggered a small tsunami (Giordano and De Astis, 2021). Medium-term(days) geophysical (Giudicepietro et al., 2020) and geochemical (Inguaggiato et al., 2019; Aiuppa et al., 2021; Laiolo et al., 2022) precursors have been identified for the paroxysm of 3 July 2019. Moreover, a period of more than a month before the paroxysm of 3 July 2019 was characterized by the occurrence of powerful gas explosions (Giudicepietro et al., 2022). This has been highlighted by a study based on the clustering of seismo-acoustic data with machine learning methods, compared with the recordings of cameras for volcanic surveillance, thanks to the relationship between the outgassing processes and the seismo-acoustic signals (Salerno et al., 2018; Giudicepietro et al., 2021; Zobin et al., 2021; Longo et al., 2023).

The present work focuses on the application of an automatic outlier detection tool to identify, in the sequence of the persistent explosive activity, any anomalous change in the monitoring parameters similar to the one that preceded the paroxysm of 3 July 2019. This tool is a hybrid method, based on the combination of two analytical techniques: 1) the Empirical Mode Decomposition (EMD); and 2) the Support Vector Regression (SVR). This hybrid technique has already been successfully applied to the identification of anomalies in the time series of radon and other geochemical and seismic parameters in the Campi Flegrei area (Sabbarese et al., 2020) and in other areas (Duan et al., 2016; Ambrosino et al., 2019; 2020a; Nie et al., 2020). This hybrid method EMD+SVR has already been tested and compared with the most common and used single outlier detection methods in the literature, such as multiple linear regression, auto-regressive integrated moving average tool, and singular spectrum analysis: the comparison revealed internal weaknesses of single methods, having poor performance in terms of computational time and higher absolute error (Ambrosino et al., 2020a). In the present work, we applied the EMD+SVR outlier detection tool to the analysis of seismic, geochemical and ground deformation parameters recorded on Stromboli over a ten–month period, including the summer 2019 paroxysmal crisis.

The data used, the proposed method and the results obtained are illustrated in the following paragraphs.

2. Data

In this work we analyze seismic parameters, deformation and geochemical data related to the period 15 November 2018 - 15 September 2019, which includes the paroxysms of 3 July and 28 August 2019, as well as the major explosion of 25 June 2019 and the effusive phase that lasted between 3 July and 30 August 2019 (Calvari et al., 2021; Giudicepietro et al., 2022). We selected this interval because in this period we have good continuity of the time series of seismic data. For this reason we did not consider extending the analysis to a longer period. The seismic parameters derive from the analysis of data acquired from the Stromboli seismic network (De Cesare et al., 2009). The seismic stations are equipped with Guralp CMG40T (0.016-50 Hz) and 3ESPC (0.008-100 Hz) broadband velocimeters sensors, the former with a sampling rate of 50 samples per second and the latter with a sampling rate of 100 samples per second (Giudicepietro et al., 2023). The seismic parameters used in this work were chosen on the basis of the results of previous works, which highlighted how they are sensitive to variations in Stromboli's eruptive style. These parameters are: fractal dimension; polarization azimuth; VLP peak to peak amplitude; VLP size; seismic amplitude; and VLP per hour. They were analyzed in the Giudicepietro et al. (2020). Furthermore, we used the time series of the seismo-acoustic clusters, which represent the typology of the prevalent ordinary Strombolian explosions defined through the clustering of the seismo-acoustic signals, carried out using a Self-Organizing Map (SOM) approach, as described in Giudicepietro et al. (2022).

Mandelbrot (1967) introduced the concept of fractals and the term fractal dimension to determine the length of the west coast of Great Britain, fractals and self-organized criticality have been widely used to study the level of complexity of many geological and geophysical phenomena (e.g. Turcotte, 2007). Mathematically, a fractal follows the relation, $N_i = \frac{C}{r_i^D}$, where N_i is the number of objects with a characteristic linear dimension r_i, C is a constant of proportionality, and D is the fractal dimension. If the fractal dimension is an integer, it is equivalent to the Euclidean dimension. In this study, we calculated time varying fractal analysis by using the Higuchi (1988) algorithm for the estimation of D using timed sequential data on 30-minute contiguous windows. The fractal dimension provides significant features that describe the complexity of the volcanic dynamics, and their time variations allow the detection of changes that can be interpreted in terms of short–term precursors of volcanic activity (López et al., 2014).

The polarization azimuth (Fig 3b) was calculated for the STRA station in Giudicepietro et al. (2020), using the Obspy system tool (Krischer et al., 2015), which is based on the estimation of the covariance matrix of the three components (vertical, east-west and north-south) of the seismic station signal and on the singular value decomposition of this matrix. The polarization analysis was applied to signal windows 30 minutes long. In the cited work, the resulting azimuth from the polarization parameter showed the most significant variations before the 3 July 2019 paroxysm. For this reason we chose to include it among the parameters used in this work.

The VLP peak-to-peak amplitude (Fig 3c) is the time series of the peak-to-peak amplitude of VLPs on the east-west component of the STRA seismic station, filtered in the 0.05–0.5 Hz frequency band. The series has a time step of 30 minutes. For each time step the value is the maximum peak-to-peak amplitude of the VLP events contained in the 30 minute time window.

The VLP size (Fig. 3d) parameter was defined in Giudicepietro et al. (2020) and is sensitive to both the durations and amplitudes of VLP events. It is based on the calculation of the maximum RSAM (Borman, 2012) estimated on a sliding window of 30 seconds, with a shift of one second, within data intervals of 30 minutes. For each 30-minute time interval the corresponding VPL size value is the maximum RSAM of the 30-second-windows contained in that interval. This parameter is calculated using the east-west component signal of the STRA seismic station, which is radial with respect to the source position of the VLPs (Giudicepietro et al., 2020), filtered in the 0.05–0.5 Hz frequency band.

The seismic amplitude (Fig. 3e) is defined here as the mean square of the 3-component module of half-hour signal windows. We used the data of the 3-component STRA station. The VLP per hour (Fig. 3f) is the daily VLP hourly rate, averaged on a monthly basis. The parameters based on a single component of the seismic signal were calculated using the east–west component of the STRA station, because it is particularly sensitive to seismic sources linked to the eruptive and degassing dynamics of the crater area (Giudicepietro et al., 2023). Additional seismic parameters are the indicators of the style of Stromboli's ordinary activity, obtained from the result of the clustering of seismo–acoustic data (Giudicepietro et al., 2022). Giudicepietro et al. (2022) analyze a set of about 14,200 explosions (the largest of every half hour from 15 November 2018 to 15 September 2019) and identify three main clusters, which, based on the analysis of the camera recordings, correspond to three different types of Strombolian explosions. The red cluster (Fig. 2g and Fig. 3g) represents well–collimated jet explosions that can reach up to 200 m in height and eject ballistic fragments. The blue cluster (Fig. 2e and Fig. 3h) represents gas explosions visible on the thermal camera as modest emissions of hot gas, without ballistic fragments, reaching a maximum height of 10 m. This cluster was dominant for at least one month before the paroxysm of 3 July 2019 and for this reason it is considered as a precursor of the paroxysmal activity. The green cluster (Fig. 2f and Fig. 3i) is related to almost hemispherical–shaped explosions, which were characterized by the maximum height of about 80 m and by the ejection of incandescent spatters with a wide range of ejection angles. Here we use the daily percentage of red, blue and green clusters, with respect to the daily total number of explosions given by the sum of the events belonging to the three clusters, as parameters indicating the style of the ordinary Strombolian activity.

Furthermore, we use the soil CO_2 flux measurements (Fig. 3l) carried out by a CO_2 permanent geochemical network based on the accumulation chamber method (Chiodini, et al., 1998; Aiuppa et al., 2010; Inguaggiato et al., 2017; 2018; 2020; Aiuppa et al., 2021; Fig. 1). Another geochemical parameter that we used in this work is the bulk SO_2 (Fig. 3m) measured with the FLAME DOAS network, which is a network of ground-based permanent sensors for the measurement of SO_2 in the plume (Burton et al., 2009; 2015; Fig. 1).

In addition, data from a Ground-Based Synthetic Aperture Radar (GBSAR) installed on the northwest side of the island (Fig. 1) have also been analysed (Fig. 3n). The data were processed using an interferometric SAR approach (GBInSAR), which provides the line-of-sight (LOS) displacement between the sensor and the target area, using the phase difference between the acquisitions to derive information on the deformation of the observed scene (Di Traglia et al., 2021). The device operates in the Ku band (17.0-17.1 mm radar), with a revisit time of 6-7 min and an image averaging time of 30 min (Di Traglia et al., 2021). The values represent the cumulative temporal evolution of the average of the measurements carried out in 30 min (max 6 measurements) of some contiguous pixels (averaged over 5 × 5 pixels, corresponding to about 100 m^2) in the crater area, with good temporal coherence, allowing the measurement of LOS displacement time series with an accuracy in displacement measurement of 0.5 mm (Di Traglia et al., 2021). For the sensor acquisition geometry (look angle and heading angle) see Di Traglia et al. (2021). Figure 3 shows all the data and parameters used in the present work.

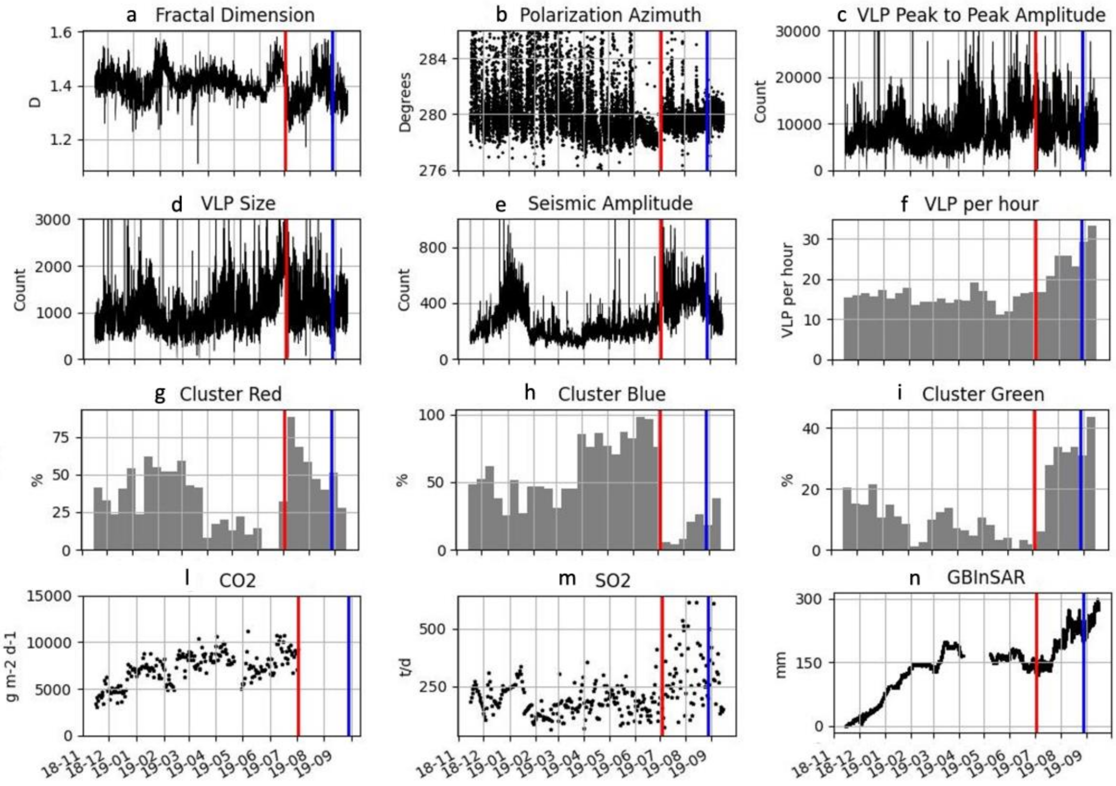

Figure 3. The time series in the period 15 November 2018 - 15 September 2019. a) the fractal dimension of STRA east component; b) the azimuth of the polarization of the unfiltered STRA signal; c) the VLP peak–to–peak amplitude calculated on the STRA east component; d) VLP size calculated for the STRA east component; e) the Mean Square Seismic Amplitude of the 3–component signal module of the STRA station; f) VLP per hour is the daily VLP hourly rate; g) daily percentage of red cluster explosions; h) daily percentage of blue cluster explosions; i) daily percentage of green cluster explosions; l) daily soil CO_2 flux; m) daily SO_2 emission from the vents; n) GBInSAR displacement. The red and blue vertical lines indicate the 3 July and 28 August 2019 paroxysms, respectively.

3. Methods

The method used to identify the anomalies in the dataset is the hybrid algorithm based on the combination of the Empirical Mode Decomposition + Support Vector Regression (EMD+SVR) (Sabbarese et al., 2020; Nie et al., 2020; Fig. 4). This algorithm merges two separate methods in order to combine the strengths of each one and achieve higher accuracy and lower uncertainty (Duan et al., 2016). The algorithm was developed in a Matlab environment, and has been well tested over the years by several scientific works (Ambrosino et al., 2019; 2020b; 2021; Duan et al., 2016; Nie et al., 2020; Sabbarese et al., 2020). In detail, the EMD technique decomposes the analysed signal into a collection of components (smoothing, noise, trend, seasonal-periodic modulations etc.). The signal is progressively decomposed in frequency until it becomes constant or monotonous. Each component is obtained as the difference between the signal and the average of the upper and lower cubic-splines interpolating the local maxima and minima, respectively. This technique is adaptive and does not require the use of a priori parameters (Fig. 4a). The full analytical description of the EMD method is reported in Duan et al. (2016). After applying EMD, the other non-parametric method, SVR, creates a regression model on each component from EMD, and lastly on their sum, by performing the least-squares fit. This technique predicts a function having the least deviation from the original signal, as flat as possible. Commonly, SVR is applied in high-dimensional dual space, using Gaussian kernel mapping function (Fig. 4b). The full analytical description of the SVR method is given by Nie et al. (2020). At this point a range of variability of the signal obtained from EMD+SVR is defined. The range is obtained with a 90% confidence interval by adding and subtracting the standard deviation divided by the square root of the signal value itself. The anomalies are then identified as residuals, i.e. the difference between the original signal and the upper (positive anomaly) or lower (negative anomaly) value of the previously defined interval at each time point (Sabbarese et al., 2020) (red circles in Fig. 4c). The choice of the 90% confidence interval adequately estimates the reliability of the anomaly results according to Anastasios et al. (2014); other confidence values (95% and 99%) were tested and then discarded as they showed no anomalies.

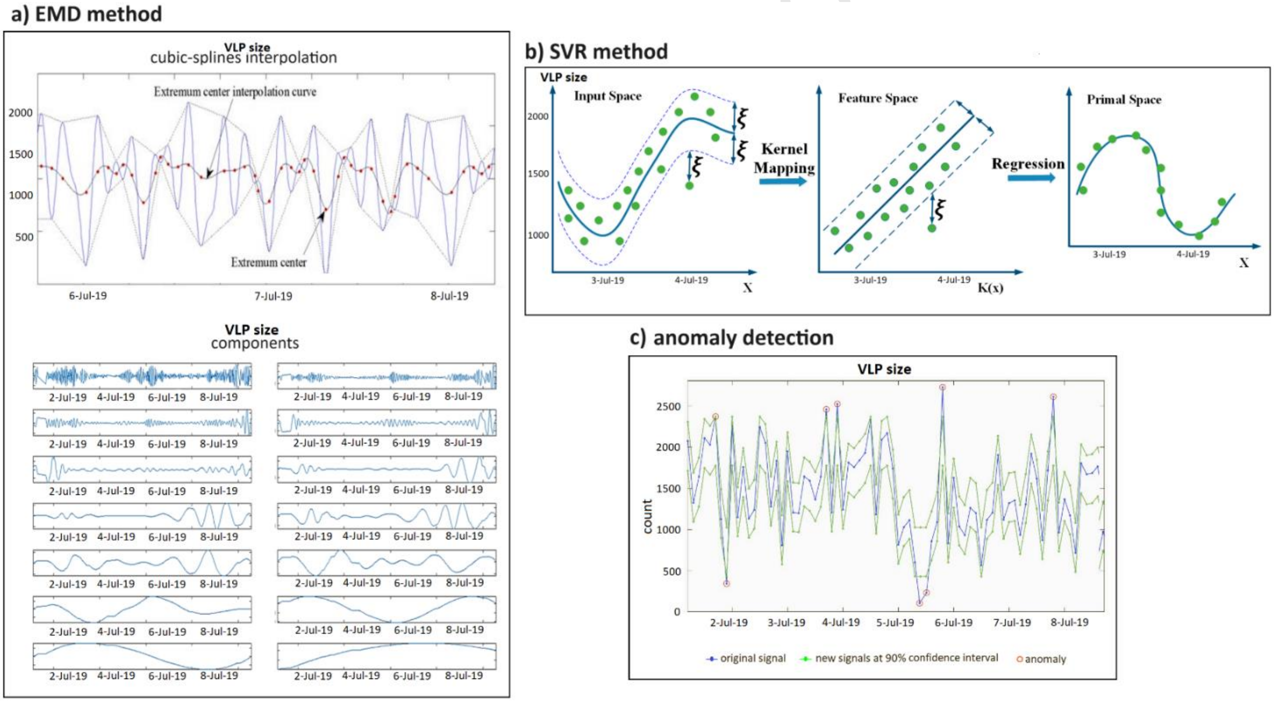

Figure 4 Graphical visualization of the operations of the hybrid EMD+SVR method on a part of the VLP size signal (2 July 2019 – 8 July 2019). a) EMD application with a focus on the cubic-spline interpolation of the upper and lower local maxima and minima of the signal, the average signal obtained, and all the components in frequency. b) SVR application on the result from EMD method: creation of a regression model, by performing the least-squares fit technique, transposed into a high-dimensional dual space by using kernel mapping. c) Anomalies identification after hybrid method EMD+SVR: the anomalies (red circles) are the values of the original signal (blue line) beyond the two new boundary signals (green lines) from the EMD+SVR method at 90% of confidence interval.

4. Results

The anomalies resulting from the EMD+SVR analysis of all the datasets investigated in this work, related to the period 15 November 2018 - 15 September 2019, are presented in Fig. 5. The anomalies underline the specific values not attributable to the normal evolution of the studied signals, and therefore are potentially indicative of pre-paroxysm activity of geochemical and geophysical parameters (see section 2. Data) related to the volcano crisis of the summer 2019. The method we have developed is designed to detect possible precursors of paroxysmal activity, and therefore it should not be sensitive to the onset of overflows. The primary goal is to identify changes in the style of ordinary Strombolian activity that indicate the ascent of gas-rich magma, which can precede violent explosive behavior. Therefore, the absence of anomalies before the overflow on December 6, 2018, aligns with our objectives. Between the end of 2018 and the beginning of 2019, the method detected anomalies that corresponded to a period of increased eruptive activity, characterized by frequent rockfall and gravel flows during intense spattering (Di Traglia et al., 2020). During this time, the intensity of ordinary Strombolian activity increased, but the eruptive style did not change significantly. For this reason, some parameters, such as VLP size, peak-to-peak amplitude, and cluster blue, showed only modest anomalies. Additional anomalies were observed between the end of March and May 2019. These anomalies were linked to brief periods of increased ordinary Strombolian activity. However, some parameters, such as fractal dimension, LOS displacement, and cluster blue, did not exhibit significant anomalies during this interval.

The anomaly identification system proposed in this study revealed a significant increase in anomalies starting from early June 2019, particularly in the parameters VLP size, mean square amplitude, fractal dimension, CO_2, and cluster blue. These anomalies, especially the blue cluster, were linked to changes in the eruptive style of ordinary Strombolian activity and were a prelude to the paroxysm phase. Basically, this period was marked by the emergence of powerful gas explosions, represented in this analysis by the occurrence of the blue cluster (Giudicepietro et al., 2022). During the pre-paroxysm period, a major explosion occurred on 25 June. Then, the first of the two paroxysms took place on 3 July 2019.

Anomalous values in the characteristics of the VLP events, both in terms of amplitude/size and frequency of occurrence, were observed around the two paroxysmal events, thus characterizing both the preparatory phase and the post-event days. In contrast, GBInSAR deformation data and the occurrence of the red cluster decreased before the 3 July 2019 paroxysm, and resumed after the end of the eruption, in a period characterized by very intense and frequent explosive activity (Di Traglia et al., 2020). Furthermore, no geochemical or deformation anomalies were observed prior to the paroxysm on August 28. These anomalies appeared briefly only after the paroxysm (Fig. 5d).

The EMD+SVR hybrid method applied to the parameters of the ordinary Strombolian activity automatically identified the anomalies related to the variations of the eruptive style before the two paroxysms of the summer 2019 recognized in previous studies (Giudicepietro et al., 2020; 2022; Inguaggiato et al., 2020; Aiuppa et al., 2021). These results are encouraging for the design of automatic data analysis systems to support the real-time monitoring of Stromboli and possibly other volcanoes. It is worth to point out that the anomalies identification in this study is not made through a threshold value, but as a residual between the original signal and the one reconstructed by the EMD+SVR method. Moreover, the hybrid method is a time varying tool, which also takes into account the signal previously used iteratively. So, it can happen that, for instance, during the effusive period no anomalies occur in the VLP size signal, becoming it the new background of the hybrid method.

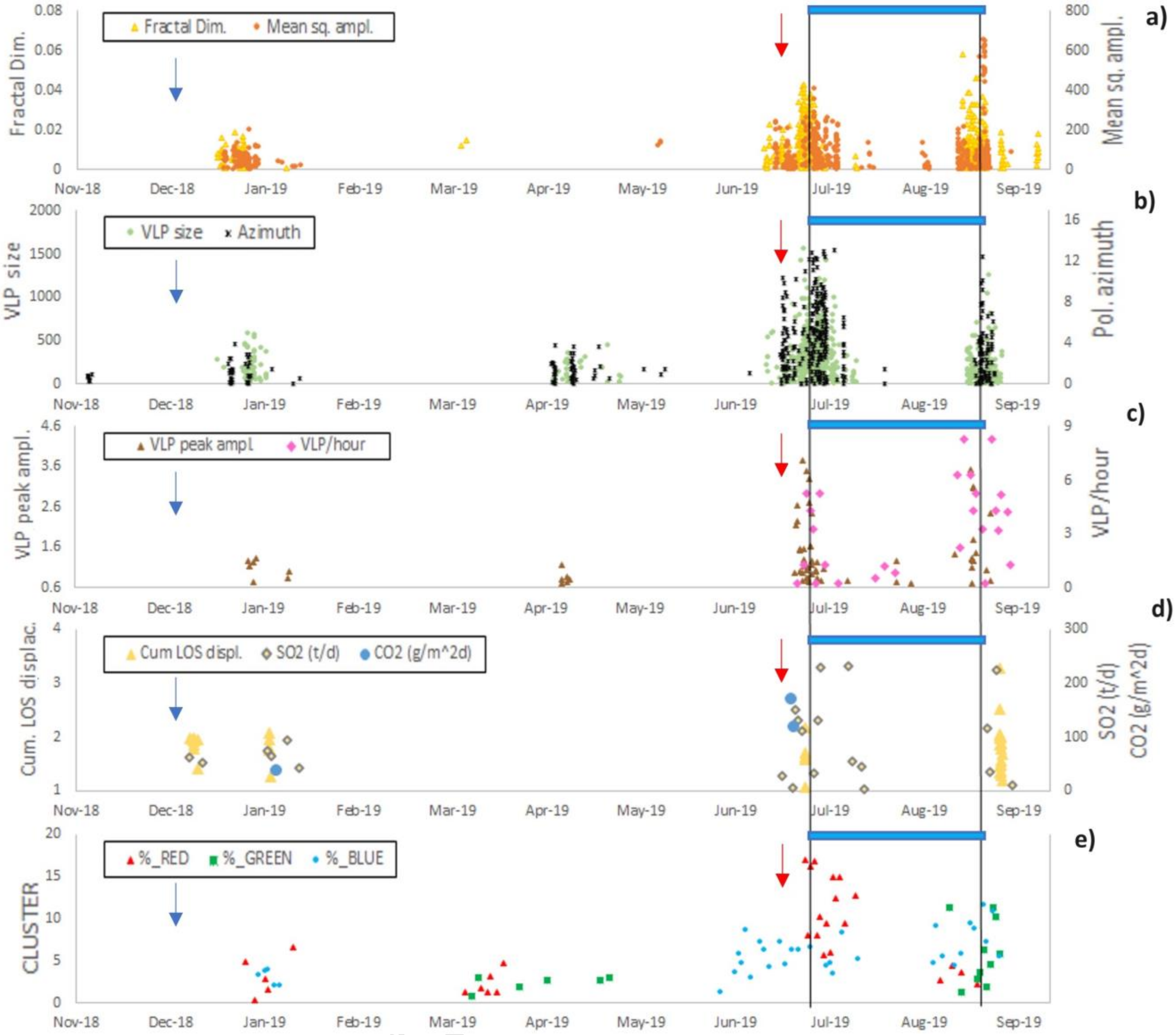

Figure 5. Comparison of the Stromboli 3 July and 28 August 2019 paroxysms (vertical black lines) with the anomalies obtained from EMD+SVR method on the analysed dataset (see section 2. Data). a) fractal dimension of STRA (Fractal Dim.), in yellow, and Mean Square Amplitude of the STRA station (Mean sq. Ampl.), in orange. b) VLP size in lite green, and azimuth of the polarization of the STRA signal (Pol. Azimuth) in black. c) peak-to-peak amplitude of the VLPs (VPL peak ampl.) in brown, and VLP/hour in pink. d) cumulative LOS displacement (cum. LOS displ.) in light orange triangles; SO_2 signal in lite yellow diamonds; CO_2 flux in dark blue; e) clustering of seismo-acoustic data in green, blue and red (cluster green, cluster blue and cluster red defined in Giudicepietro et al., 2022, respectively). The blue arrow indicates the overflow which occurred on 6 December 2018. The red arrow indicates the major explosion on 25 June 2019. The blue horizontal bar indicates the duration of the effusive phase of July-August 2019.

5. Discussion and conclusions

The 2019 eruption had a serious impact on the island, also causing the death of a tourist, and highlighted the need for more specific and advanced methods to monitor the variations in Stromboli's eruptive activity. For this reason, in recent years, research efforts have been directed towards the identification of volcanological, geophysical, and geochemical anomalies that preceded the 2019 explosive events (Giudicepietro et al., 2020, 2022; Aiuppa et al., 2021; Romano et al., 2022). These studies demonstrated that, even if changes in the intensity of ordinary Strombolian activity were not detected before the paroxysmal phase, some changes in Stromboli's eruptive style were recognized at least one month before the paroxysm of 3 July 2019. This suggests the possibility of strengthening and improving the monitoring of Stromboli, which poses challenges common to the monitoring of other persistently active volcanoes (e.g., Etna, Italy; Volcano de Fuego, Guatemala; Sakurajima, Japan; etc.). However, to obtain an improvement of the monitoring systems of Stromboli, chosen as a case study in this work, and potentially of other very active volcanoes such as those mentioned above, we need effective automatic analysis methods for the estimation of significant parameters, which characterize the state of activity of the volcano, and also for the analysis of the time series they constitute, in order to highlight the onset of anomalies. In this frame, we have developed and tested our hybrid method obtaining encouraging results. In our specific application, the method was designed to detect paroxysms based on findings from previous studies (e. g., Giudicepietro et al., 2020; 2022), which identified clear precursors to the first paroxysm on July 3, 2019. The most indicative parameters for imminent paroxysms are those related to VLPs (e. g. VLP size, VLP peak–to–peak amplitude and also the fractal dimension which has been interpreted, in Giudicepietro et al., 2020, as a parameter linked to the VLP component of the seismic signal), as the VLP signal is generated by the movement of gas slugs within the conduit, making it a robust indicator of the volcano's degassing processes. In particular we have found that the time series of the fractal dimension and the VLP size are particularly useful for identifying anomalies that indicate changes in volcano activity. Among the geochemical parameters, both the SO_2 and CO_2 time series show significant anomalies in the days preceding the paroxysm of July 3. Furthermore, the CO_2 anomaly was particularly sensitive to the approach of the paroxysm and less to the variations that occurred in December 2018, which did not culminate in an eruptive event other than ordinary Strombolian activity. Moreover, this method, applied to the results of seismo-acoustic clustering of Strombolian explosion types, allowed us to gain insights into the volcano's behavior and eruptive style changes. The hybrid method presented here can be easily implemented for highlighting anomalies of physical parameters also in other environmental context, as it is a general anomaly search method that can work on time series of different types of data (Duan et al., 2016; Ambrosino et al., 2019; 2020a; Nie et al., 2020). In this study we developed a prototype system that used parameters automatically generated with ad hoc procedures. These procedures are not included in the routine analysis of Stromboli monitoring data, but they are potentially implementable, even in real time, for most parameters, having low computational costs. For this reason, the method is suitable for the automatic identification of anomalies also in the data time series of other active volcanoes (Sabbarese et al., 2020). The parameters to be considered for the search for anomalies are particularly important. In fact, every volcanic context can be characterized by particular phenomena, which generate geophysical and geochemical signals that are significant for understanding the state of the volcano. This method can be implemented automatically, providing the possibility of having meaningful information for defining the state of activity of a volcano in real time, and it can be a valid support to help in evaluations and decisions. For this reason, the hybrid method can contribute to the safety of communities living in volcanic regions and to increase our understanding of volcanic processes.

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Author Statement

- I confirm that the manuscript has been shared with all the contributors
- I declare that me and all the authors have no competing interests to declare
- I declare that no use of AI and AI-assisted technologies was made in writing the manuscript

Dear Editorial Board,

The authors declare that they have no conflicts of interest.

Highlights

- The combination of the Empirical Mode Decomposition (EMD) and the Support Vector Regression (SVR) creates a hybrid method suitable for discovering anomalies in geophysical data.

- The EMD+SVR hybrid method is able to detect the anomalies that preceded the 2019 Stromboli paroxysmal phase.

- The hybrid EMD+SVR method can easily be implemented for automatic analysis of monitoring data from other volcanoes