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(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

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Hot-spot detection and characterization of strombolian activity from MODIS infrared data

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30	Detection and characterization of variable thermal regimes at Stromboli volcano
31	from MODIS infrared data
32	

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41 Identifying and characterizing strombolian activity from space is a challenging task for satellite-42 based infrared systems. Stromboli volcano is a natural laboratory that offers a unique opportunity 43 for refining thermal remote sensing applications that involve transient phenomena and small to 44 moderate hot-spots. A new simple and fast algorithm gave us the opportunity to revisit the 45 MODIS-derived thermal output at Stromboli volcano in the last 13 years. The new algorithm 46 includes both nighttime and daytime data and shows a high performance with the detection of 47 small-amplitude thermal anomalies (< 1 MW), as well as a low occurrence of false alerts (< 4%). 48 Here, we show that the statistical distribution of Volcanic Radiative Power (VRP; in Watt) is 49 consistent with the detection of variable activity regimes that we subdivided into six levels of 50 thermal activity: Very Low (VRP < 1 MW), Low (1 MW < VRP < 15 MW), Moderate (15 MW < 51 VRP < 80 MW), High (80 MW < VRP < 315 MW), Very High (315 MW < VRP < 1000 MW), 52 Extreme (VRP > 1000 MW). The "Low" and "Moderate" thermal levels are associated to 53 strombolian activity and reflect fluctuations of the magma level within the conduit feeding the 54 activity at the surface. The "High" and "Very High" levels of thermal output represent the bulk 55 thermal emissions during periods of effusive activity. The most highly level ("Extreme") is 56 reached only during the onset of flank eruptions (occurred on 28 December 2002 and 27 February

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57 2007). We found that the retrieved thermal levels are in general agreement with the explosive 58 levels evaluated at Stromboli since 2005, and their correlation has been shown to be dependant on 59 the observed activity (i.e. eruption onset, lateral flank effusion, summit overflows, strombolian 60 activity). The specific hot spot detection system presented here allow us to characterise thermal 61 emissions in terms of different levels of volcanic activity, to decode the thresholds separating 62 them and to depict long term eruptive dynamics at open-vent volcanoes.

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1. Introduction

In the last decade thermal remote sensing techniques have been increasingly applied for monitoring active volcanoes. Ramsey and Harris (2013) give an overview of these applications, discussing the limits of several satellite-based infrared sensors to detect and track volcanic hot-spot. Actually, many of these studies are concentrated in developing near real time automated techniques thus quantifying the heat released and the related mass fluxes (Ganci et al., 2012).

A variety of algorithms were developed for detecting volcanic hot spots using different satellites and sensors, such as GOES (e.g. Harris et al., 1997), AVHRR (e.g. Harris et al. 1995; Tramutoli 1998), MODIS (e.g. Flynn et al. 2002; Wright et al. 2002), SEVIRI (Hirn, Di Bartola, and Ferrucci 2009; Ganci et al., 2011). A comprehensive review of these techniques, including their performance and applicability, is given by Steffke and Harris (2011). According to the authors, these algorithms may be subdivided into four main groups on the basis of their detection principles. These are:

- *fixed threshold*: which use the data on a single pixel to assess whether the radiance or
 temperature, is anomalous (i.e. Flynn et al., 2002, Wright et al. 2002);
- (ii) *contextual*: it uses the difference between a pixel's radiance (or temperature) and the
 surrounding pixels to assess the presence of an hot spot (i.e. Harris et al, 1995; 2001;
 Harris, Pilger, and Flynn 2002; Higgins and Harris 1997; Kaneko et al., 2002; Webley et
 al., 2008; Galindo and Dominguez, 2003);

- (iii) *temporal*: it compares a pixel's radiance (or temperature) with mean values obtained for
 the same pixel from time series of data (i.e. Di Bello et al., 2004; Pergola, Marchese, and
 Tramutoli 2004);
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(iv) *hybrid*: it combines two or more of the above principles (i.e. Dean et al., 1998; Dehn, Dean, and Engle 2000; Kervyn et al., 2006; Hirn, Di Bartola, and Ferrucci 2009; Koeppen, Pilger, and Wright, Glaze, and Baloga 2011).

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89 In their review Steffke and Harris (2011) concluded that each algorithm operates well within the 90 limits and criteria of its design requirement. For example, a global detection system such as 91 MODVOLC (Flynn et al., 2002, Wright et al. 2002) has a lower efficiency in detecting hotspots, but 92 favours the processing of a large amount of data in near real time. On the other hand, the algorithm 93 based on the simple temporal principles (i.e. the RST technique of Di Bello et al., 2004) may be 94 more efficient in detecting local small hotspots, but requires more complex data processing and is 95 somehow inefficient to provide a continuous record of persistent, stationary thermal anomalies 96 (Koeppen, Pilger, and Wright 2011, Steffke and Harris, 2011). The efficiency of any hot-spot 97 detection system may effectively change in function of the observed volcanic activity. Effusive 98 eruptions are easier case to be detected since they represent volcanic targets with high surface 99 temperatures and widespread thermal anomalies (lava flows). Conversely, hot-spots detection over 100 active lava domes is more challenging since these bodies have smaller planar dimensions and cooler 101 lava surfaces (Wright, Glaze, and Baloga 2011). Moreover, the persistence of a thermal anomaly is 102 a further complication for space-based hot-spot detection. For instance, short-lived phenomena 103 (such as explosions or short paroxysms) produce transient thermal signals with small probabilities 104 of being detected. If these events are associated to a small size hot emitters (i.e., a volcanic vent 105 and/or vents), they represent critical targets. For these reasons the detection of "strombolian 106 activity" from space represent one of the challenging task for satellite-based infrared systems (e.g., 107 Coppola et al., 2012).

Stromboli is an open-system volcano, located in the Aeolian islands (Southern Tyrrhenian Sea; Figure 1) well known for its permanent volcanic activity considered as a reference case for classifying minor to intermediate volcanic eruptions (e.g., Newhall and Self, 1982). Volcanic activity is essentially strombolian, with continuous explosions and mild eruptions of scoriae, lapilli, ash and bombs (Rosi, Bertagnini, and Landi 2000) at summit vents. This activity may be sporadically replaced by lava effusions and more energetic explosions with the eruption of larger volumes of tephra, named "paroxysms" (Barberi, Rosi, and Sodi 1993).

115 At Stromboli, the climate is temperate with higher temperatures reaching 36-40 °C during the 116 summer (July) and minima temperatures of 0-4 °C during the winter time (December and January). 117 The rainfall is not abundant and widely distributed in about 50-90 days a year of rain with a peak in 118 the cold season. The month with the lowest number of rainy days is July, whereas December and 119 January have the highest number of rainy days (cf., Laiolo et al., 2012). The sky is clear for 35% of 120 the days in spring, 70% in summer, 50% in the fall and 25% in the winter. Snow has been rarely 121 observed at the summit of the volcano (924 m asl). Due to the peculiar volcanic activity and its 122 temperate climate Stromboli volcano may be considered as a natural laboratory for refining infrared 123 remote sensing applications.

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- 125

Figure 1

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In this paper we describe a new algorithm, specifically developed for hot-spot detection at Stromboli volcano. Thus, the new algorithm is addressed to detect small thermal anomalies and contains spectral (threshold), spatial (contextual) and temporal principles well compatible with the so-called "*hybrid*" approach (e.g., Koeppen, Pilger, and Wright 2011). Here, we analyze more than a decade of MODIS data collected on Stromboli by revisiting and updating the earlier analyses of Coppola et al. (2012). After showing the algorithm performance, we will show how the long term thermal records may be used to define distinct thermal regimes that characterize the recent activityof Stromboli.

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2. The algorithm

The algorithm uses MODIS level 1b data acquired by NASA's Terra (launched on December 1999) and Aqua (launched on May 2002) satellites that normally image Stromboli volcano four times per day (since May 2002). The whole data set (from March 2000 to March 2013), consisting of more than 19000 images, has been analysed following several main steps. These are: (*i*) Data Extraction, (*ii*) Resampling, (*iii*) Definition of Region of Interest (ROIs), (*iv*) hot-spot detection (*v*) calculation of the Volcanic Radiative Power (VRP).

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2.1. Data Extraction from MODIS level1b granules

The first step is dealing with the extraction of the data from the MODIS level1 granules. These data consist of the date and time of satellite overpasses, the satellite viewing geometry (zenith and azimuth), the location of each pixel (Latitude and Longitude) as well as the Digital Number (DN) related to the spectral bands of interest:

149	(i)	Reflectivity of band 1 (R_1), centred at 0.645 µm (for daytime image on	ly)
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- 150 (ii) Reflectivity of band 2 (R_2), centred at 0.858 µm (for daytime image only)
- 151 (iii) Radiance of band 6 (L_6), centred at 1.64 μ m (for daytime image only)
- 152 (iv) Radiance of band 21 (L_{21}), centred at 3.959 µm (Low-gain MIR channel)
- 153 (v) Radiance of band 22 (L_{22}), centred at 3.959 µm (High-gain MIR channel)
- 154 (vi) Radiance of band 31 (L_{31}), centred at 11.03 µm (TIR channel)
- 155 (vii) Radiance of band 32 (L_{32}), centred at 12.02 µm (TIR channel)

The DN of each selected band is firstly scanned to filter-out any missed or "corrupted" datum. According to the MODIS Level 1B Product User's Guide (Toller, Isaacman, and Kuyper 2006) this is achieved by eliminating, for each band, all the pixels with DN > 32,768 (i.e., the invalid data values), with the exception of the pixels with DN = 65,533 (saturated values), used in the subsequent steps.

162 The georeferred data are also scanned to remove the bow-tie effect that, at the edge of the swath,163 produces the so called "scan to scan" overlapping (Nishihama et al. 1997).

Once the effects of invalid and bow-tie related pixels have been removed, we used the conversion coefficients for each selected band (scale and offset) in order to convert the DN into reflectivity and/or radiance data (for details regarding this step see the MODIS Level 1B Product User's Guide).

Finally, we build up a corrected spectral band centred at 3.959 μ m (hereby called band L_{21ok}), by using the L₂₁ or L₂₂ radiance, depending on band 22 saturation (or not), respectively.

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2.2. Resampling of original data and production of NTI maps

Cropping and resampling of the original Level1b MODIS data is necessary for two main reasons. First because high scan angles contribute to the growth of the projected ground spatial element (up to approximately 10 km² for scan angles of 55°; Nishihama et al. 1997). This leads the radiance of a potential sub-pixel hotspot to be integrated over a variable area, thus introducing a further source of error in estimating its thermal output. Secondly, because the hot-spot detection scheme, described below, requires an image-to-image registration, similar to application of the RST technique (cf. Di Bello et al. 2004; Pergola, Marchese, and Tramutoli 2004).

Thus, we cropped and resampled (into an equally-spaced 1 km grid) the MODIS level1b data which fall within a mask (50 x 50 km) centred over the summit of Stromboli volcano (Figure 2(*a*)). This means that one hot-spot pixel, whose area was 2 km² in the original image, become two pixels with

182 equal areas of 1 km^2 in the resampled image.

Once the radiances data has been resampled we calculated the Normalised Thermal Index (NTI) for
each pixel according to Wrigth et al. (2002):

185
$$NTI = \frac{L_{21ok} - L_{32}}{L_{21ok} + L_{32}}$$
(1)

186 These *NTI* maps enhance the presence of any sub-pixel hotspot and represents the reference 187 matrices to the further steps of the algorithm.

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Figure 2

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2.3. Regions of Interest

A main step in the processing flowchart is the definition of three Regions Of Interest (ROIs) within the resampled NTI maps. These are centred on the volcano summit (where strombolian activity is taking place) and are normally concentric (see Figure 2(b)). The ROI₁ consists of an outer ring (measuring 50 x 50 km) and includes the island of Panarea as well as the sea surrounding Stromboli. The ROI₂ represents an intermediate region (15 x 15 km) essentially characterized by the sea surrounding the island of Stromboli. Finally, the ROI₃ (5 x 5 km) samples the island of Stromboli itself, including the coast lines and small portions of its near-shore sea.

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2.4. Hot Spot detection

The algorithm is based on the characterization of the natural variation of the *NTI* (seasonal effect) within each ROI. For example in Figure 2 we plot the *NTI* time-series relative to the nighttime pixels of each ROI during 2006. Note that within this plot, the thermal anomalous pixels (hot-spot contaminated) tend to increase their *NTI*, whereas the presence of thick and cold clouds has the opposite effect and tend to lowering their relative values (negative spikes).

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The seasonal variation of the NTI is clear in the three regions although some anomalous pixel is consistent with the presence of some hot-spot within ROI_3 (Figure 3(*a*)).

In the next sections we describe the algorithm subdivided for nighttime and daytime data,respectively.

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2.4.1. Nighttime algorithm

To detect an hot-spot within the nighttime images we firstly defined two fluctuating thresholds (named NTI_{thresh1} and NTI_{thresh2}, respectively) that envelop the natural variation of the NTI within the whole image (including ROI₁, ROI₂ and ROI₃; Figure 2(b)) in absence of thermal anomalies and/or cloud covering. These thresholds are obtained by using the form of a typical sinusoidal function which can be described by:

220

221
$$NTI_{thresh} = A \sin\left[\frac{2\pi}{P} \left(-\alpha\right] + C$$
(2)

222

where *A* is the yearly amplitude of the *NTI* variation, *P* is the length of each cycle (II/days), *t* is the time of satellite overpass (julian day), α is the phase shift (i.e., the day when the curve crosses the baseline as it ascend), and *C* is the baseline, here represented by the average yearly *NTI* value.

To set the appropriate parameters for the two thresholds (Equation 2), it is necessary to process at least one year of data. Hence, the operator may chose the appropriate values of A, α and C by excluding the pixels clearly contaminated by hot-spot and clouds (with *NTI* values that clearly deviate from the seasonal trend). The values assumed for Stromboli volcano are summarised in Table 1 with their relative *NTI* thresholds plotted in Figure 3. These two thresholds define three fields on the *NTI* timeseries, where the upper and lower fields represent the sectors where hot-spot contaminated and cloud contaminated pixels are surely present (Figure 3).

At this point a pixel is considered "alerted" (hot-spot contaminated) if at least one of the followingtest is successfully passed.

The first test is applied to all the pixels of an image (NTI_{ROIS}) and requires that the NTI is higher than $NTI_{threshI}$:

$$Alert1 = NTI_{ROIS} > NTI_{thresh1}$$
 [Test 1]

239

The second test is applied for detecting exclusively the smallest thermal anomalies of ROI₃ having an *NTI* comprised between *NTI*_{thresh1} and *NTI*_{thresh2}. This is achieved by comparing the *NTI* of each ROI₃-pixel (not previously alerted by the Test 1) with some statistical parameters retrieved from a selected suite of "reference-pixels" appertaining to ROI₂. In particular, these "reference-pixels" (NTI_{Ref2}) are the ROI2 pixels which satisfy the following condition:

245

246

$$NTI_{Ref2} = NTI_{thresh1} > NTI_{RO12} > NTI_{thresh2}$$
 [Condition 2]

247

Hence according to condition 2, we defined "reference-pixels" all the pixels of ROI_2 which have the NTI comprised between the two thresholds previously defined ($NTI_{thresh1}$ and $NTI_{thresh2}$). In other words, NTI_{Ref2} exclusively includes the pixels surrounding Stromboli volcano that are not contaminated by hot-spots or clouds.

From these reference pixels we thus calculate the maximum value (NTI_{Max2}), mean (NTI_{Mean2}) and the standard deviation (NTI_{std2}) which are the parameters used to define the second test:

254

$$Alert2 = (NTI_{ROI3} > NTI_{Max2}) \& [NTI_{ROI3} > (NTI_{Mean2} + 3 \times NTI_{std2})]$$
[Test 2]

Therefore, Test 2 settles that a pixel of ROI_3 , in order to be considered hot spot contaminated, must have an *NTI* higher than the value obtained by considering the natural variability of the surrounding region (ROI_2).

The total number of "alerted" pixels (*Alert*) is finally obtained by considering all the pixels passing
the Test 1 (*Alert1*) or the Test 2 (*Alert 2*).

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2.4.2. Daytime algorithm

264 The detection of hot-spot during daytime overpasses is much more complicated due to two main reasons. First, because the radiance in the MIR channel (L_{21ok}) is particularly affected by solar 265 266 reflection effects (Wright et al., 2002). Solar reflection perturbs the NTI as well, especially for 267 pixels that are sampling reflective surfaces (i.e. water, snow, sand, clouds, etc.), thus causing an increase in its value due to the reflected solar energy (Wright et al., 2002). Secondly, because 268 269 during daytime the solar heating may effectively enhance the contrast between vegetated and non-270 vegetated areas. This will produce apparently higher NTI values over volcanic (non-vegetated) areas 271 when compared with the surrounding (vegetated) areas. These intrinsic effects, may cause a 272 problematic discrimination of genuine volcanic hot-spot since during daytime all the pixels in non-273 vegetated areas have NTI values that naturally exceed the surrounding background.

In the attempt to reduce the effects of solar reflection we apply a correction to the L_{21ok} radiance (on the resulting *NTI*) based on the co-registered radiance recorded on band 6 (L_6). Following Wright et al., 2004 for daytime data we thus corrected the radiance at 4µm (L_{21ok}) by subtracting 4.26% of the energy radiated at 1.6 µm (L6) (assumed to be the solar reflected component). The corrected NTI thus becomes:

279

280
$$NTI_{corr} = \frac{(L_{21ok} - (0.0426^* L_6)) - L_{32}}{(L_{21ok} - (0.0426^* L_6)) + L_{32}}$$
(3)

282 The comparison between the un-corrected and corrected NTI, relative to the 2006 day-time data is 283 shown in Figure 3. In Figure 4(a), the un-corrected NTI shows an extremely noisy signal in all the 284 ROIs, overprinted on the typical seasonal trend. The noise introduced by solar reflection 285 (represented by spikes) is particularly evident on ROI_1 and ROI_3 , both related to the reflective sea 286 surface. On the other hand, the application of Equation (3) (solar correction) produces a clear 287 attenuation of these signals enhancing the filtered seasonal pattern. Notably, the seasonal trend and 288 the absolute values of the NTI_{corr} relative to ROI₁ and ROI₂ (Figure 4(b)) become very similar to 289 those recorded during nighttime overpasses (compare Figure 3(b) and 4(b)). This similarity suggest 290 that the trend recorded by NTIcorr is almost exclusively affected by the seasonal variation of the sea 291 surface temperature (thermal inertia of the sea makes the diurnal changes in temperature less 292 pronounced than on land) and increases our confidence that solar contamination has been removed 293 by applying Equation (3).

This is also confirmed by looking at the NTI_{corr} trend of ROI₃ that from April to October (i.e., during the hot season) is "diverging" from ROI₁ and ROI₂. Such a decoupling can be explained by the increase of the temperature gradient occurring between the summit, non-vegetated, volcanic areas (essentially affected by the solar heating) and the surroundings.

We therefore define a single daytime *NTI* threshold (*NTI*_{thresh3}) that allows us to discriminate between the solar heating effects and the presence of a genuine volcanic hot-spot. As previously, we used Equation (2) to describe the seasonal *NTI*_{thresh3} trend (Figure 4(*b*)). The parameters for calculating *NTI*_{thresh3} are summarized in Table 1. We thus flagged a thermal alert whenever a daytime pixel satisfies the following test:

303

304

$$Alert3 = NTI_{ROIS} > NTI_{thresh3}$$
 [Test 3]

305

306 As it will be discussed later, the capability of detecting hot-spot during daytime is much more 307 reduced when compared to the application of the nighttime algorithm. This results in poor detection

308	rates during periods of low strombolian activity. However, during periods of more vigorous thermal
309	activity, as well as during the effusive eruptions, the results of the daytime algorithm will strongly
310	integrate the dataset recorded during nighttime overpasses (cf., Tables 2 and 3).
311	
312	Figure 4
313	
314	2.5. Volcanic Radiative Power
315	When a pixels is flagged as <i>alert</i> , the "above background" at $4\mu m$ radiance (ΔL_{4PIX}) is calculated
316	as:
317	
318	$\Delta L_{4PIX} = L_{4alert} - L_{4bk} \tag{4}$
319	
320	where L_{4alert} is the 4 μ m radiance of the alerted pixel/s and L_{4bk} is the background radiance at 4 μ m.
321	This last, L_{4bk} , it is estimated from the arithmetic mean of all the pixels surrounding the alerted one
322	(or around the alerted cluster) not contaminated by clouds. Accordingly, cloudy pixels were
323	detected using the method described by Giglio et al., (2003) so that:
324	
325	<i>cloud</i> = $[BT_{11} < 255]$ [Condition 4; for nighttime data]
326	or
327	<i>cloud</i> = $[(R_1+R_2)>0.9]$ or $[BT_{11}<245]$ or $[((R_1+R_2)>0.9)$ & $(BT_{11}<265)]$ [Condition 5;
328	for daytime data]
329	
330	where BT_{11} is the brightness temperature (in K) of band 11 (retrieved from L_{11} using the Plank's
331	function), and R_1 and R_2 are the reflectivity of bands 1 and 2, respectively.

Following Wooster, Zhukov, and Oertel (2003), we calculated the Volcanic Radiative Power (*VRP* in W) by means of the MIR method. Hence, for any individual alerted pixels, the VRP_{PIX} is calculated as:

335

$$VRP_{PIX} = 18.9 \times A_{PIX} \times \Delta L_{4PIX}$$
(5)

337

338 where A_{PIX} is the pixel size (1 km² for the resampled MODIS pixels).

339 When two or more pixels (a cluster of pixels) are alerted, the total radiative power is finally 340 calculated as the sum of the single VRP_{PIX} , so that:

341

$$VRP = \sum_{1}^{nalert} VRP_{PIX}$$
(6)

343

344 where *nalert* is the number of alerted pixels.

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3. Algorithm performance

347 Due to the differences of the nighttime and daytime alert detection procedures, the two algorithms348 must be considered separately when testing their performances.

To test the performance of the nighttime algorithm, we followed the methodology of Steffke and Harris (2011) and we visually inspected all the *NTI* images in order to identify the presence of a real hotspot ("Manual" alerts, Table 2). These hand-picked images were used as a reference benchmark for comparing these results with those obtained by using the algorithm (see algorithm alerts in Table 2). This is computed in terms of how many automatic detections are effectively consistent with those manually identified (cf. "Correct" in Table 2). Hence, the difference between the "Manual" and the "Correct" detections represents the "Missed" detections (Table 2). Finally, when the algorithm detected a hotspot that was not validated by visual inspection, we classified it as a"False" detection (cf. Table 2).

The results of this comparison, are shown in Table 2 where the total number of detections (and their relative percentage), are subdivided year by year. In addition, in Figure 5 we also show a typical NTI map for each detection case (Correct, Missed and False detections).

361

Figure 5

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362

The overall comparison suggests that the nighttime algorithm perform correctly on ~79% of the "Manual" detections, with ~22% of "Missed" cases, and less than 4% of "False" alerts (Table 2). Noticeably, all the "False" detections consist of small amplitude thermal anomalies (i.e. VRP < 2MW), and they could be easily eliminated by setting a cutoff at 2 MW. However, such a cutoff will also produce a strong reduction of the efficiency of the algorithm, with the "Correct" detections decreasing from ~79% to less than 59%. Since most of the "False" detections are low-amplitude ones, we preferred to keep some false alerts than missing several real hotspots.

371 The excellent performance of the nighttime algorithm is also evident by means of comparing the frequency of alerted detections retrieved both manually ($f_{alertManual} = N_{alert,Manual}/N_{Overpasses}$) and 372 automatically ($f_{alert,algorithm} = N_{alert,algorithm}/N_{Overpasses}$) (Figure 6(a)). The best linear fit plots close to 373 374 the 1:1 ratio (with $R^2 = 0.97$), thus suggesting an excellent agreement over the whole range of f_{alert} . However, the percentage of "Correct" detections seems to be affected by the level of volcanic 375 activity (Figure 6(b)), which is basically correlated with the frequency of detection ($f_{alert,algorithm}$). 376 377 This means that the algorithm is most highly efficient during effusive phases, whereas it reduces its 378 performance during periods of weak to moderate strombolian activity. From Table 2 it also appear 379 that the number of "False" detection it is not correlated with the level of activity and remain 380 typically around four cases per year.

382

Figure 6



384 The overall effectiveness of the nighttime algorithm can be finally compared with the results 385 obtained by Coppola et al., (2012) which analyzed nighttime MODIS data at Stromboli volcano 386 between 2000 and 2012 with a different algorithm. In our previous paper (Coppola et al., 2012) we 387 found 743 alerts during 9635 overpasses, with an average frequency of alert detection 388 $(f_{alert}=N_{alert}/N_{Overpasses})$ equal to 8.5%. Over the same period the new algorithm (section 2.4.1) 389 detected 1332 alerts (f_{alert} =15%; Table 2), thus doubling the detection capability (particularly for 390 small-amplitude thermal anomalies) with respect to our previous algorithm (Coppola et al., 2012). 391 For comparison, during 2000-2012 the MODVOLC system (which use a simple fixed threshold) 392 detected at Stromboli volcano 442 nighttime alerts (f_{alert} =4.5%), half of which identified during the 393 effusive periods of activity.

394

395

Figure 7

396

397 Testing the performance of the daytime algorithm is more problematic, due to the difficulty in 398 discriminating "false" and "real" hotspot using the visual inspection of each image. As previously 399 discussed, this difficulty relies on solar heating effects, so that discriminating a genuine volcanic 400 hot-spot from a pixel "naturally" hotter than its surrounding is rather challenging. This is 401 particularly true for low-amplitude thermal anomalies, whose radiance in the MIR channel may 402 exceed only moderately from their background values. Therefore, there are no effective benchmarks 403 for testing the daytime algorithm despite visual data inspection. However, this procedure it is useful 404 to exclude by eye the presence of evident "False" detections.

405 An alternative approach to evaluate the daytime algorithm takes into account the nighttime 406 detections as a reference thermal signal. We thus plotted separately the *VRP* retrieved from 407 nighttime and daytime data (Figure 7). In particular, we compared the results for a period of high

thermal emissions (the first seven months of 2003 effusive activity; Figure 7(a)) with those 408 409 obtained for a year of lower thermal emissions (characterized by low to mild strombolian activity 410 during 2009; Figure 7(b)). In both the cases, the trends of thermal outputs confirm an excellent 411 agreement between the two dataset (daytime and nighttime). Notably, during the effusive phase the 412 daytime algorithm performed very well in terms of mean VRP (the average value of the VRP 413 measurements) as well as in tracking the general trend of the eruptive sequence (Figure 7(a)). 414 However, the number of daytime detections was almost halved with respect to the nighttime 415 detections, likely due to the minor efficiency of the algorithm in detecting small thermal anomalies. 416 The minor sensitivity of the daytime algorithm is also evident by comparing the dataset recorded 417 during one year of typical strombolian activity (i.e. during 2009; Figure 7(b)). The general trend of 418 daytime data is still consistent with the fluctuations of thermal outputs recorded during the night. 419 However, the number of alert detections obtained by applying the daytime algorithm drastically 420 decreased. Again these results demonstrate the limits of the daytime algorithm which is unable to 421 detect smaller hotspots. In fact the daytime dataset consist of 364 alerts over a total of 9599 422 overpasses, which gives a mean f_{alert} equal to 4% (Table 3). This compares with a frequency of alert 423 detection of 15% for nighttime images thus enhancing the different efficiency in hotspot detection 424 of the two algorithms.

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4. Statistical analysis of VRP and thermal regimes

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We here focus our analysis on the nighttime dataset for statistical reasons. This dataset consists of a
large number of observations (1445 data) and shows a higher efficiency in detecting small thermal
anomalies.

431 As a whole, the entire nighttime dataset indicates that *VRP* is ranging from < 1 MW to more than 432 3000 MW, thus spanning over three orders of magnitude. Particularly, its frequency distribution is 433 extremely peaked and skewed toward higher values, as shown in Figure 8(*a*). A useful way to visualise the shape and properties of such kind of positive, asymmetric distributions consists in
transforming the original data (*VRP*) into log-transformed data (log[*VRP*]). This procedure was
previously used to identify distinct thermal regimes at Stromboli and Nyamuragira volcanoes
(Coppola et al., 2012; 2013).

438 Our new dataset for Stromboli volcano (log(VRP) records) reveals the presence of two main 439 regimes that intersect around 30 MW (logVRP=7.5; Figure 8(b)). Similarly, Coppola et al., (2012) 440 found that a VRP of ~50 MW marks a change in the eruptive style of Stromboli, basically identified 441 with the transition from strombolian-dominated to effusive-dominated activity. The small 442 discrepancy between the two thresholds is likely due to the higher sensibility of the new algorithm 443 which is able to detect a larger number of small thermal anomalies (see chapter 3). However our 444 analysis remains consistent with those previously provided by Coppola et al. (2012) and confirm the presence, at Stromboli volcano, of two main thermal regimes (strombolian and effusive) 445 446 overlapping at 30-50 MW.

447 Considering the modal value of each regime (the most frequent value), we here estimate that 448 strombolian and effusive activities are characterised by a typical *VRP* of 4 MW (logVRP=6.6) and 449 100 MW (logVRP=8), respectively. Based on this simple relation we may roughly infer that the 450 energy radiated during twenty-five years of strombolian activity is almost equivalent to those 451 realised during one year of effusive activity.

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Figure 8

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A deeper investigation on the *VRP* distribution can be achieved by plotting the log-transformed data (log(VRP)) within a normal probability plot (Figure 9). Here, a population of events (or observations) log-normally distributed follows a straight line, as showed by the black dashed line (Figure 8). Though the most of the dataset follows approximately this kind of distribution we suggest that some minor inflection points, separating groups of data, may be regarded as changing points indicative of distinct radiating regimes. The inferred inflection points appears around 1, 15,
80, 315 and 1000 MW and defines six main radiating regimes hereby named Very Low, Low,
Moderate, High, Very High and Extreme (Figure 9).

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Figure 9

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The "Very Low" radiating regime (*VRP* < 1 MW) represents about 17 % of the data and includes essentially the most of the false alerts detected by the algorithm. However, in the 75% of the cases the detection of a Very Low regime represents a genuine hotspot which may be associated to the presence of a single vent (with a radius of ~ 1 m and temperature of 950°C) within the summit area of Stromboli.

471 The "Low" radiating regime (1 MW < VRP < 15 MW) is the most represented group, comprising 472 more than 55% of the data. This regime consist of the bulk thermal emissions associated to the 473 "typical" strombolian activity typically characterized by persistent degassing and frequent explosive 474 events occurring at one to 15 open vents (Harris and Stevenson, 1997).

475 This regime gradually shifts toward the "Moderate" radiating regime (15 MW < VRP < 80 MW) 476 that is represented by about 15% of the data. The "Moderate" regime is typical of periods with more 477 vigorous strombolian activity which may evolve into short periods of sustained spattering and/or 478 fountaining or eventually summit overflows (Coppola et al., 2012). We regard the "Moderate" 479 regime as a transitional state (between strombolian and effusive) characterised by the uprising of the 480 magma column that is feeding the active vents. Eventually this regime may prelude the transition 481 into a pure effusive phase (flank eruption) as observed before the 2002-2003 and 2007 eruptions 482 (Coppola et al., 2012).

483 The transition from "Moderate" to "High" thermal regimes marks a clear change in the eruptive 484 style of Stromboli, leading to lava effusion (Figures 9). The "High" radiating regime (80 MW <485 *VRP* < 315 MW) is represented by 10% of the data and it has been observed during the second 486 phase of the 2002-2003 eruption (from mid-February 2003 to July 2003) as well as during the most 487 of the summit overflows recently occurred at Stromboli (Coppola et al., 2012). Notably, during 488 these periods the effusion of lava typically occurred at a rates $< 1m^3s^{-1}$ (Calvari et al., 2005, Ripepe 489 et al., 2005, INGV Report 2011-08-02).

490 Conversely, the "Very High" radiating regimes (315 MW < VRP < 1000 MW) has been recorded 491 during the initial phases of the 2002-2003 major eruption (from January to mid-February 2003), as 492 well as during the 2007 eruption and some major, long-lived overflows (such as those of December 493 2012 (Figure 9). The "Very High" regime includes only 2% of the observations and it is always 494 associated with sustained lava effusion with a discharge rates of 1 to 5 m³ s⁻¹ (Marsella et al., 2009; 495 Calvari et al., 2010).

496 Finally, the highest thermal regime (hereby defined as "Extreme"; VRP > 1000 MW) has been 497 recorded only two times during the last fourteen years on 28 December 2002 and on 27 February 2007 (Figure 9). In particular, these cases, that represents only 0.1% of the data, where recorded 498 499 few hours after the beginning of the two major flank eruptions and marks the onset of the main effusive phases. In these cases, lava discharge rate were higher than 10 m³s⁻¹ (Calvari et al., 2005; 500 501 Neri and Lanzafame, 2008), and accompanied the initial and very fast emplacement of lava flows 502 along the "Sciara del Fuoco". We thus infer that the detection of such high VRP (>1000 MW) likely 503 indicates the onset of a flank eruption at Stromboli volcano. A complete timeseries of VRP recorded 504 between 2000 and 2012 (nighttime data only) is shown in Figure 10 where the colour of each 505 detection (stem) is function of the ongoing thermal regime.

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Figure 10

5. Discussion

Coppola et al., (2012) reported that all the detection above 50 MW were coeval with major episodes 511 512 of spattering and lava overflows. However, the whole cross validation of the thermal activity levels 513 described above is challenging due to limited field observations and related reports. To overcome 514 these problems and to better understand the thermal regimes and their bearings with volcanic 515 activity levels, it is worth to compare thermal MODIS outputs with the explosive levels recorded 516 (on a daily basis since 2005) by the Laboratorio di Geofisica Sperimentale of the University of 517 Florence (cf., http://lgs.geo.unifi.it/) and sent to the Italian Civil Protection Department (DPC). The 518 explosive level is based on a data set of geophysical parameters (seismic, infrasound, number of 519 explosions, deformation) recorded for over a decade: it is subdivided into five levels, representing 520 an average assessment of the explosive intensity (i.e., 0 - Not determined; 1 – Low; 2 – Moderate; 521 3 – High; 4 – Very high). The timeseries reported in Figure 11, indicates an overall correlation 522 between thermal and explosive levels (such as their averages on a weekly basis), with a general 523 increase of the thermal output during periods characterised by high explosive activity.

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- 525

Figure 11

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527 However, this comparison also suggests that different periods, or different types of activity show 528 rather peculiar links between thermal and explosive levels. This is particularly evident by plotting 529 the explosive levels vs. the thermal levels, as shown in Figure 12. Here, several distinct fields may 530 be visualised: each one of them characterises a specific type of volcanic activity or eruptive period. 531 For instance, the onset of the 2007 effusive eruption was characterized by an "extreme" thermal 532 level, associated to a "very high" explosive level (star in Figure 12). Conversely, the subsequent 533 flank effusion was characterised by very high thermal levels coeval with a low explosive activity 534 (red circles). This particular relationship was likely due to the sharp ceasing of the explosive 535 activity at summit vents, due to the propagation of an effusive fracture down to the central part of 536 NE flank; this event drained the lava out of the crater area and was followed by a sharp decrease in

537 geophysical and geochemical parameters (e.g., Ripepe et al., 2009; Cigolini et al., 2013). An 538 additional case is given by the major summit overflows that occurred between 2008 and 2012 539 (black arrows in Figure 11). Here, the high thermal levels were associated to a moderate-high 540 explosive activity (black circles), thus suggesting that summit outflows were accompanied to a 541 sustained explosive activity. Finally, the dataset suggests that the ratio between thermal and 542 explosive levels were somehow different during the 2005-2006 and the 2008-2012 eruptive periods 543 (blue and pink circles, respectively): after the 2007 eruption the thermal to explosive ratio was 544 generally higher than before the eruption, thus suggesting that some changes occurred in the 545 eruptive dynamics.

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6. Conclusions

Figure 12

550 We have developed a new algorithm which is specifically addressed to the detection of small hot 551 spot associated with thermal anomalies typical of strombolian activity. In particular, the new 552 algorithm was developed on the basis of the constant position of thermal anomalies that 553 substantially coincides with the active summit vents. Moreover, it includes principles of contextual, 554 temporal and spectral hot spot detection approaches/methods. The application of this algorithm in 555 analyzing Stromboli activity is very efficient (up to 95 % of correct alerts) and reduces the rate of 556 false alerts (typically around four per year), especially when applied to nighttime data. The high efficiency in tracking small hot spot (< 1 MW), coupled with the analysis of MODIS derived 557 558 thermal records for over a decade, gave us the opportunity to build up an exhaustive dataset of 559 volcanic radiative power (VRP) measurements. Notably, the frequency distribution and the 560 probability plot of these thermal records allows the definition of distinct radiating regimes which 561 are closely associated to different levels of volcanic activity. We thus suggest that the refinement of 562 a near real time processing scheme allow us to discriminate, on the basis of satellite-based thermal

563 monitoring, the changes in strombolian activity: such as, for instance, the occurrence of summit 564 overflows as well as the possible onset of lateral flank eruptions. Finally, we trust that a wise 565 comparison of the retrieved thermal outputs with other geophysical and geochemical parameters, is 566 an additional key-factor for better understanding the eruptive dynamics at Stromboli. However, 567 similar approaches could be taken in monitoring other persistently active volcanoes.

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581

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 composition of terrestrial lavas from space". *Geology* 39: 1127-1130.
- 704
- 705 Appendix 1

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List of parameters and specific definitions used in the algorithm

Parameter	Definition	Explanation
ROIs	Region of Inerest (s=1,2 or 3)	
NTI	Normalised Thermal Index	Equation 1 applied pixel per pixel on nighttime images
NTI corr	Normalised Thermal Index corrected for solar reflection	Equation 3 applied pixel per pixel on daytime images
NTI ROIS	NTI of pixels within ROIs	Equation 1 applied to the pixels of ROIs
NTI_{Ref2}	Reference pixels of ROI2	Pixels of ROI2 satisfying Condition 2
NTI Max2	Maximum NTI of NTI _{Ref2}	
NTI Mean2	Mean NTI of NTI_{Ref2}	
NTI Std2	Standard deviation of NTI_{Ref2}	
NTI thres1	Empirical upper NTI threshold (nighttime algorithm)	Equation 2 with parameters settled in Table 1
NTI thres2	Empirical lower NTI threshold (nighttime algorithm)	Equation 2 with parameters settled in Table 1
NTI thres3	Empirical upper NTI threshold (daytime algorithm)	Equation 2 with parameters settled in Table 1
Alert1	Alerted pixel(s)	Pixel(s) flagged as "alert" using Test 1 (nighttime algorithm)
Alert2	Alerted pixel(s)	Pixel(s) flagged as "alert" using Test 2 (nighttime algorithm)
Alert3	Alerted pixel(s)	Pixel(s) flagged as "alert" using Test 3 (daytime algorithm)
cloud	Cloudy pixel(s)	Pixel(s) considered as "cloudy" using Conditions 3 and 4
L 4alert	MIR radiance (at 4mm) of alerted pixel(s)	
L_{4bk}	Backgound MIR radiance (at 4mm) of alerted pixel(s)	arithmetic mean of all the pixels surrounding the alerted one (or around the alerted cluster) not contaminated by clouds
ΔL_{4PIX}	"Above background" MIR radiance of alerted pixel(s)	Equation 4
VRP PIX	Volcanic Radiative Power of alerted pixel(s)	Equation 5

Tables

738TABLE 1 - Parameters used to define the NTI thresholds (Equation 2)739

Parameter	Unit	NTI _{Thresh1}	NTI _{Thresh2}	740 741 NTI _{Thre} م
				744
A [NTI variation]	adimensional	0.02	0.02	0.07 745
P [cycle length]	day ⁻¹	π/183	π/183	746 π/183747
α [phase shift]	day	121	121	$106 \frac{748}{749}$
C [NTI baseline]	adimensional	-0.865	-0.915	-0.82 ⁷⁵⁰ 751
				
				753
				754

Year	Overpasses	Manual ^a	Algorithm ^a			
				Correct ¹	Missed ¹	False ²
	no.	no. (%)	no. (%)	no. (%)	no. (%)	no. (%)
2000	339	37 (10.9)	32 (9.4)	25 (67.6)	12 (32.4)	7 (21.8)
2001	406	14 (3.4)	16 (3.9)	10 (71.4)	4 (28.6)	6 (37.5)
2002	597	72 (12.1)	54 (9.0)	50 (69.4)	22 (30.6)	4 (7.4)
2003	818	386 (47.2)	370 (45.2)	364 (94.3)	22 (5.7)	6 (1.6)
2004	833	77 (9.2)	46 (5.5)	45 (58.4)	32 (41.6)	1 (2.2)
2005	836	70 (8.4)	43 (5.1)	39 (55.7)	31 (44.3)	4 (9.3)
2006	819	124 (15.1)	99 (12.1)	91 (73.4)	33 (26.6)	8 (8.1)
2007	822	197 (24.0)	179 (21.8)	175 (88.8)	22 (11.2)	4 (2.2)
2008	827	166 (20.1)	127 (15.4)	125 (75.3)	41 (24.7)	2 (1.6)
2009	835	199 (23.8)	140 (16.8)	140 (70.3)	59 (29.6)	0 (0.00)
2010	836	103 (12.3)	84 (10.0)	83 (80.6)	20 (19.4)	1 (1.2)
2011	837	179 (21.4)	142 (17.0)	138 (77.1)	41 (22.9)	4 (2.8)
2012	830	155 (18.7)	113 (13.6)	110 (71.0)	45 (29.0)	3 (2.6)
TOTAL	9635	1779 (18.5)	1445 (15.0)	1395 (78.4)	384 (21.6)	50 (3.5)

TABLE 2 - Summary of the nighttime alerts detected manually ("Manual") and automatically by the algorithm

a - percentages are calculated as the number of detections over the number of the overpasses

1 - percentages are calculated from the fraction of "Correct" and "Missed" detections, with respect to the

"Manual" detections

2 - percentages are calculated from the fraction of "False" detections with respect to the "Algorithm" detections

Year	Overpasses	Algorithm		
	no.	no.	% ^a	
2000	320	3	0.9%	
2001	397	2	0.5%	
2002	574	13	2.3%	
2003	809	172	21.3%	
2004	813	11	1.4%	
2005	842	5	0.6%	
2006	830	11	1.3%	
2007	836	48	5.7%	
2008	842	11	1.3%	
2009	848	27	3.2%	
2010	821	15	1.8%	
2011	823	28	3.4%	
2012	844	18	2.1%	
TOTAL	9599	364	3.8%	

TABLE 3 - Summary of daytime thermal alertsdetected by the algorithm

a - percentages are calculated as the number of detections over the number of the overpasses

811 Figure Captions

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813 Figure 1. Location of Stromboli volcano in the Southern Tyrrhenian sea,

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Figure 2. (a) Example of *NTI* Map obtained from nighttime images (acquired on June 16, 2006 over
Stromboli). Note the thermal anomalous pixels (bright pixels) over the summit of the volcano; (b)
Regions of Interest (ROIs) defined for the hot-spot detection scheme (see text for explanation).

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Figure 3. (*a*) *NTI* time-series for the 2006 nighttime data over Stromboli. Each point represents the *NTI* of a single pixel. Different colors refer to the three distinct ROIs (see the electronic text for the colors). The two sinusoidal lines envelop the fluctuations of the *NTI* due to the seasonal trend; (*b*) The same NTI time-series with the alerts detected by the algorithm overlapped. *Alert1* and *Alert2* are obtained using the Test 1 and 2 respectively (see the text for explanation). For colors refer to the electronic copy.

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Figure 4. (*a*) *NTI* time-series relative to the 2006 daytime data over Stromboli. Each point represent the *NTI* of a pixel. The different colors refers to the three distinct ROIs (see the electronic version for the colors); (*b*) the *NTI* timeseries corrected for solar reflection according to the Equation (3). The alerts detected by the daytime algorithm (obtained using the Test 3) are overlapped. For colors refer to the electronic copy.

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Figure 5. (*a*) Zoomed view of selected nighttime *NTI* map (ROI2 and ROI3 only) recorded on February 12, 2006; any anomaly is visible over Stromboli volcano and the island appears cooler than the surrounding area. Three other examples of nighttime NTI maps represent the following cases: Correct (b), Missed (c) and False (d) detections (resulting from the nighttime algorithm). The
squares marks the location of the Correct (red), Missed (blue) and False (white) pixels. For colors
refer to the electronic copy.

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Figure 6. (*a*) Relationship between the frequency of alert detection retrieved manually ($f_{alert,Manual}$) and automatically ($f_{alert,algorithm}$); (*b*) percentage of "Correct" detection as a function of $f_{alert,algorithm}$. The algorithm performs almost optimally during period characterized by $f_{alert,algorithm} > 0.5$.

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Figure 7. (*a*) Comparison of thermal outputs during 2003 (a) and 2009; (*b*) the nighttime algorithm
(blue) and the daytime algorithm (red) are reported. For colors refer to the electronic copy.

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Figure 8. (*a*) Frequency histogram of *VRP* data recorded during 2000-2013 (nighttime only); (*b*) frequency histogram of log-transformed data (logVRP) enhancing the presence of two main regimes associated to the strombolian and effusive activity, respectively. These two regimes intersect at about 30 MW (logVRP=7.5).

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855 Figure 9. Probability plot of logVRP. Black dashed line represent the best fit regression by 856 assuming a pure lognormal distribution. The vertical lines represent the inferred inflection points used to define 6 distinct thermal regimes: very low, low, moderate, high, very high and extreme 857 858 thermal outputs. Note that the two VRP recorded during the onset of the effusive flank eruption 859 (violet stars) are the only "extreme" values detected between 2000 and 2013. The threshold of 30 860 MW is in the middle of the Moderate regime, which is ascribed to the transition between 861 strombolian-dominated and effusive-dominated activity, respectively. For colors refer to the 862 electronic copy.

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Figure 10. *VRP* timeseries (on log scale) recorded at Stromboli between 2000 and 2013. Different colours refer to the thermal regimes previously defined (see the text for explanation). The red horizontal line is the threshold at 30 MW separating the strombolian activity from lava effusion. For colors refer to the electronic copy.

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870 Figure 11. Thermal activity levels (left axis; red line) and explosive levels (right axis; gray bars) 871 recorded between 2005 and 2012. The different colour scales on the two axes refer to thermal 872 regimes (obtained by MODIS, left hand-side) and explosive regimes (right hand-side, evaluated by 873 the Laboratorio di Geofisica Sperimentale of University of Florence; http://lgs.geo.unifi.it/) based 874 on multiparametric recordings (seismic, infrasonic, number of explosions, deformation). The black 875 arrows indicate the timing of major overflows. The occurrence of the February 2007 eruption is 876 marked by a sharp increase in thermal levels coeval with a decrease in explosive activity. For 877 colours refer to the electronic copy.

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Figure 12. Scatter-plot of explosive vs. thermal levels of activity recorded at Stromboli between
2005 and 2012. Note how different kind of activities (such us eruption onset, effusive flank
eruption, major overflows, etc.) fall within different fields (see text for details). For colours refer to
the electronic copy.

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Fig. 1



15.213° E

891 Fig. 2









Fig. 4

















Fig. 8









Fig. 10









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