Reconstructing the 2014-2015 Fogo Island (Cape Verde) eruption through thermal remotely sensed images

Vasco de Pina Aresta Branco Miranda

Instituto Superior Técnico, Lisboa, May 2018

Abstract

The present work consists on the study of the 2014-2015 eruption of the Fogo volcano (Cape Verde) through the use of high temporal resolution imagery (from MODIS), with thermal analysis capability. The main goal of this study is to provide additional information to that coming from the analysis of high spatial resolution sensors, like Landsat8_OLI, Cosmoskymed or Pleiades, benefiting from the large quantity of data provided by the MODIS high temporal resolution. This additional information could then be used to make more reliable predictions about lava flow direction and intensity throughout the days between two high spatial resolution images.

The methodology used is based fixed threshold hot spot detection algorithms, namely MODVOLC. The results of the application of this methodology are measured on the capability of describing the eruption intensity over time (temporal analysis), assessing the position of the hot spots detected by the method in comparison to the lava position in high spatial resolution images to the same day (spatial analysis) and to assess the capability of the method to describe non-eruptive periods without falsely detect volcanic hot spots (context analysis). The optimal fixed threshold determined through the integrated study of the three analyses, results in the value of -0.82 to better describe the phenomenon.

Keywords: Fogo, thermal remote sensing, hot spot detection, NTI, fixed threshold

1. Introduction

On November 23rd of 2014, there was a volcanic eruption on Fogo Island (Cape Verde) that would last for 78 days, until February 8th of 2015 [1] [2] [3]. This event resulted in the loss of goods and infrastructures and in the reallocation of about 1000 people who lived in the nearby area. There were no human casualties [4]. This type of events are hazardous to people living in the areas affected but are also a chance to get some insight about the Earth's dynamic processes [5].

Being a phenomenon in which there is heat flux due to the release of lava and gases, volcanic eruptions can be easily detected by thermal remote sensing and its principles, most notably the Planck and the Wien laws [6].

Several sensors on board multiple satellites have the technical designations required to study such type of volcanic events. The combined analysis of data from these multiple sensors results in a wider collection of data with different types of spectral, spatial and temporal resolutions. The study of only one type of data would result in a narrower understanding of the event and it phases [5]. Having that in mind, although MODIS imagery are the main data source, data with lower temporal resolution but higher spatial resolution from Landsat8_OLI, EO1-ALI, EO1-Hyperion and Copernicus reports were also directly used for comparison. SEVIRI data, a meteorological satellite with low spatial resolution but with 15 minutes of temporal resolution was used as well, though its processing was executed by Mathieu Gouhier, as it is described in his article [8].

2. Data

The main focus of this study lies in MODIS imagery. Thus, 76 MODIS images were identified that covered the Island during the eruption period. 15 images from Landsat8_OLI, EO1-ALI and EO1-Hyperion that fulfilled the requirements (covering the island during the eruption time frame) were also available. In addition to those images, 17 Copernicus emergency reports were also used. These reports come with a collection of vectorial contours (shape files) of the island and of the lava flows for several days of the eruption.

All data was georeferenced and co-registered, though some slight adjustment were made to some MODIS images due to errors resulting from the island location within the total image frame (the error is greater, the further the study area is from the center of the image as described by Wright et al. [9]). To make these adjustments, the image captured by Landsat8_OLI on October 23rd of 2014 and the island's shape from the Copernicus reports were used as references (figure 1).

a)

b)

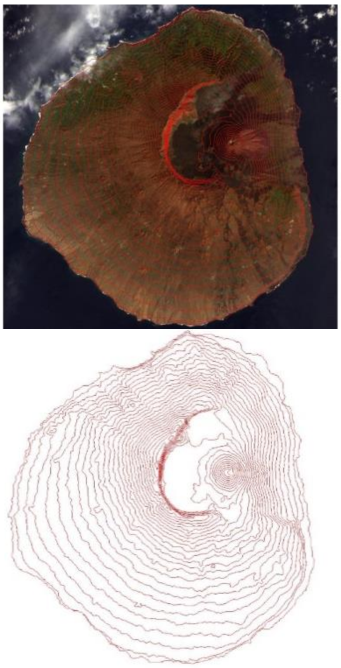

Figure 1 – a) Landsat8_OLI on October 23rd of 2014; b) island's shape from the Copernicus reports

3. Methodology

The methodology developed in this study is mainly based on the fixed threshold hot spot detection algorithm, MODVOLC [9]. Like in MODVOLC, only nocturnal MODIS images are used (to avoid the impact of diurnal solar radiation) and its implemented Normalized Thermal Index (NTI).

$$NTI = \frac{22 - 32}{22 + 32} \tag{1}$$

Or:

$$NTI = \frac{21 - 32}{21 + 32} \tag{2}$$

Through equation 1 (equation 2 when band 22 is saturated), the NTI produces a new image in gray scale that highlights the existence of sub-pixel hot spots (hotter pixels = brighter pixels). The MODVOLC algorithm proceeds then to implement the threshold found to be the one that produces lesser amount of false positives to the global scale, -0.80, so that all pixels above that threshold are flagged as thermally anomalous.

The NTI threshold of -0.80 is selected to work on a terrestrial global scale being considered in some cases "too conservative" [10]. So, unlike MODVOLC, 4 thresholds (-0.78, -0.8, -0.82 and -0.84), throughout 3 different performance analyses were tested.

Firstly, the capability of the thresholds to describe the eruption's intensity by comparing the number of identified pixels in each day, to the values of lava flow rate calculated from SEVIRI data was assessed. This analysis consists in the temporal analysis of the method. Then, every MODIS image for each day in which there is a high resolution image or a lava contour shape to the same day, or day right after, is also compared. This analysis consists on the spatial analysis of the method.

Lastly, all thresholds were tested on non-eruptive period MODIS images to assess the capability of not producing false positives. This analysis was the context analysis. The entire process behind the methodology is illustrated in figure 2:

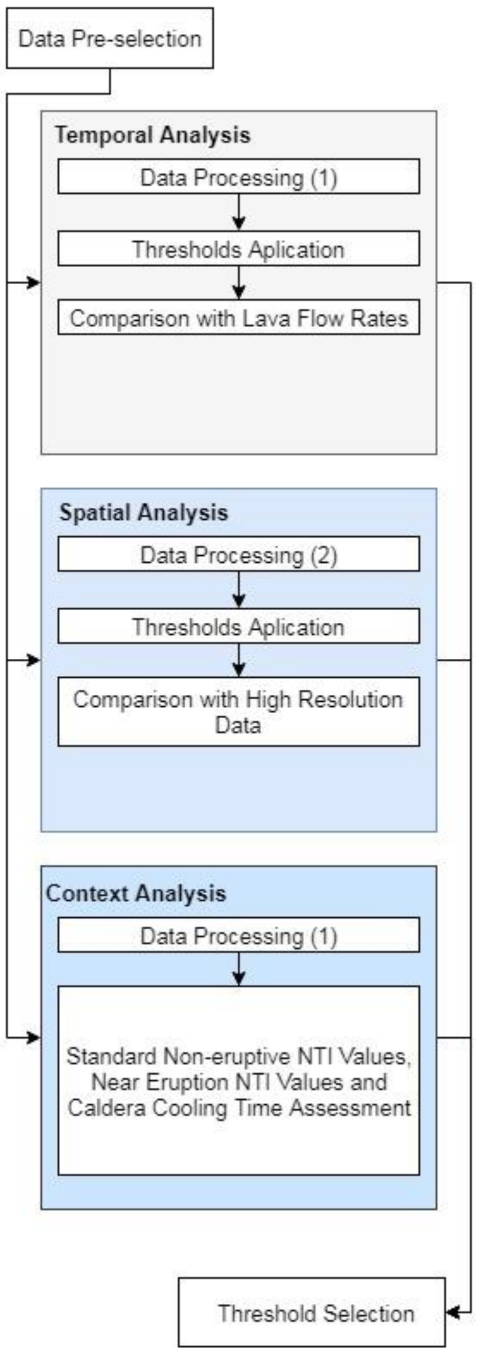

Figure 2 - Methodology flow-chart; (1) image selection, crop and NTI calculation; (2) image selection, crop, NTI calculation and co-registration

4. Results

As seen in the methodology, the results can be divided in three main instances, regarding the three types of analyses.

4.1 Temporal analysis

For this stage of the work, only MODIS images that did not present extensive cloud cover, for which the outline of the island's coast is visible or, at least, in which the caldera is visible (due to being considerably hotter than the remainder island) were admitted. Thus, this selection resulted in 54 of the 76 dates in which there is enough image quality to be regarded in this study.

The selected images were cropped and the NTI calculation was done to each. Four thresholds were tested on each MODIS image and the number of pixels flagged was counted. The number of flagged pixels was compared to the maximum value of lava flow rate for the same day, obtained from SEVIRI data and processed by Mathieu Gouhier [8] (as seen in figure 3, for the threshold of -0.80), and the number of correct and false identification were counted for each threshold (as seen in table 1).

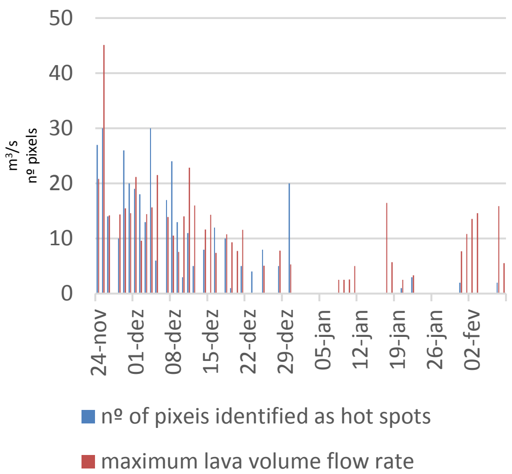

Figure 3 – Number of flagged pixels by threshold of -0.80 and value of maximum lava volume flow rate comparison for each of the 54 days considered in this analysis.

Table 1 – Results of the hot spot identification for each threshold for the 54 days

		Thresholds			
		-0.78	-0.80	-0.82	-0.84
Identifications	True Positives	28	29	31	33
	False Positives	1	1	4	9
	True Negatives	12	12	9	4
	False Negatives	13	12	10	8

For the four thresholds studied, there exists a good relation between the number of identified pixels and the magnitude of daily maximum lava flow volume rate for the first days of the eruption until the beginning of January. Concerning the results of table 1, the extreme threshold values (-0.78 and -0.84) are the least interesting, as expected. For instance, the days in which there are lava flows and there are no pixels flagged are too conservative (too much False Negatives, that is, many missing detections), being verified the opposite in the days in which there are no lava flows and there are pixels flagged (too many False Positives). This information alone is not enough to choose the best threshold, therefore, scatterplots were plotted for each threshold between the number of flagged pixels and the average lava volume flow rate (as seen in figure 4, for the threshold of -0.80).

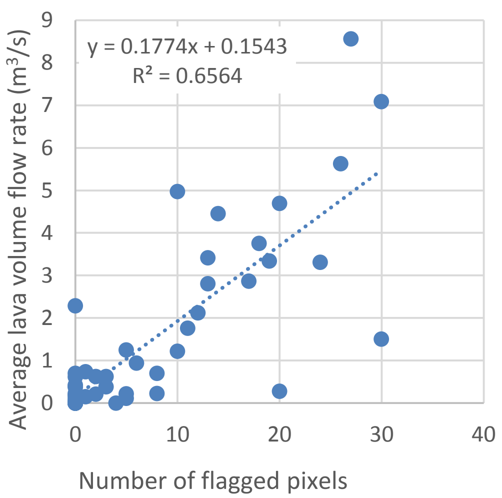

Figure 4 – scatterplots between the number of flagged pixels and the average lava volume flow rate for the threshold of -0.80. In order to determine a correlation between the two parameters, a trend line was calculated and its slopes were then compared to determine the best threshold. As illustrated in figure 5, the best correlation is achieved when the threshold is equal to -0.82, presenting the highest correlation value of 0.6971, being thus considered, for the purposes of this analysis, the best threshold.

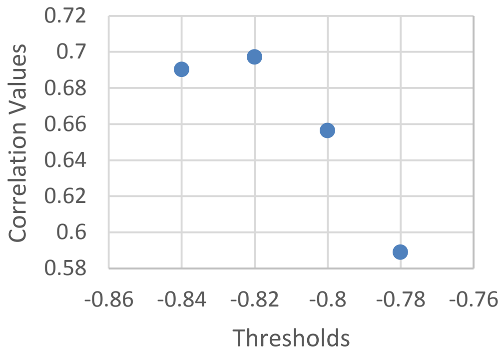

Figure 5 – variation of the correlation between the number of flagged pixels and the average lava volume flow rate for each threshold

4.2 Spatial analysis

The study of quality of spatial data provided by the method in the identification of the volcanic hot spots was based on the comparison of the location of flagged pixels whit that of lava in higher resolution images or Copernicus' lava contours to that given day (or at least, the day after). This made the number of analyzed images narrower than in the previous analysis. Due to the special focus of the analysis, the accepted quality of the MODIS imagery is higher resulting in fewer images. The remaining images were co-registered to the references (figure 1) to improve the comparison. This results in the study of 6 image pairs, being 3 between MODIS images and other sensors and 3 between MODIS images and 3 shapes (table 2).

Table 2 – Image pairs used in the spatial analysis

MODIS images	Higher resolution satellites
24/11/2014	Landsat8_OLI: 24/11/2014
16/12/2014	EO1-ALI: 16/12/2014
18/01/2015	EO1-Hyperion: 17/012015
MODIS images	Shapes from Copernicus
26/11/2014	26/11/2014
25/12/2014	25/12/2014
28/12/2014	28/12/2014

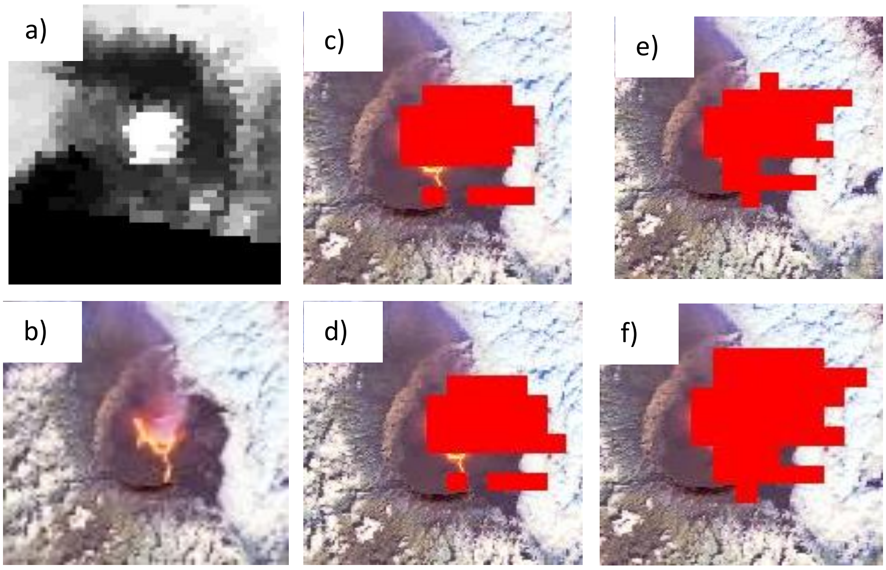

Figure 6 – Comparison between hot spot pixels' location whit lava position for all four thresholds (-0.78; -0.80; -0.82; -0.84):

a) NTI of MODIS image taken on 24/11/2014; b) Landsat8_OLI image taken on 24/11/2014 (color band combination 7-6-5); c) threshold of -0.78; d) threshold of -0.80; e) threshold of -0.82; f) threshold of -0.84

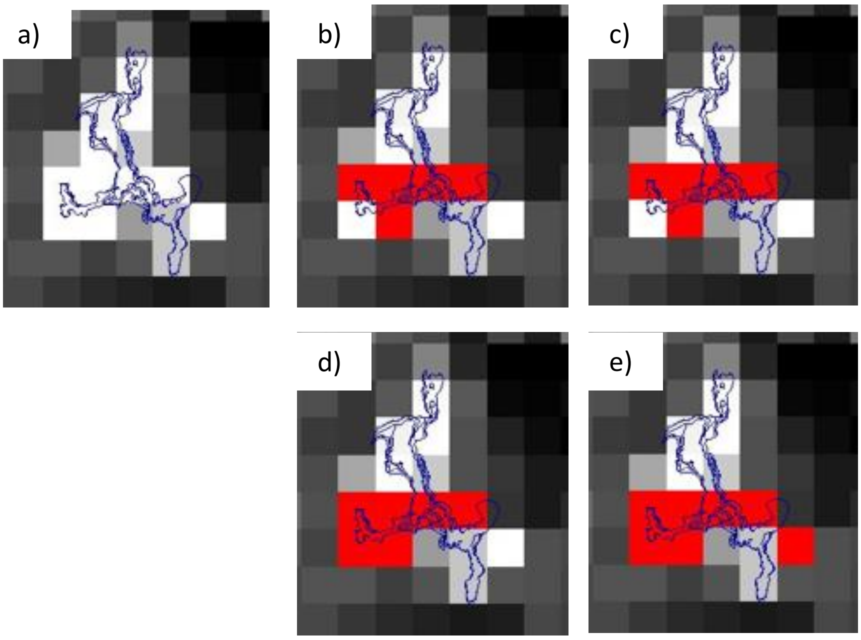

Figure 7 - Comparison between hot spot pixels' location whit lava position for all four thresholds (-0.78; -0.80; -0.82; -0.84):

a) NTI of MODIS image taken on 28/12/2014 and lava's shape for the same day from Copernicus; b) threshold of -0.78; c) threshold of -0.80; d) threshold of -0.82; e) threshold of -0.84

The process of comparison that was executed for all 6 pairs of images (table 2) is illustrated in figures 6 and 7. For all the pairs, the -0.78 threshold was found to be the worse to identify hot spots, not providing less false detections than the -0.80 threshold for all but one case (one more false detection on 26/11/2014). In the case of the -0.84, this threshold was found to be the less selective of all thresholds, introducing false positives without the correct detection of any additional true hot spot for most cases (there are two pairs in which this does not happen, but there are no changes from the previous threshold, -0.82). Between the two remainder thresholds, -0.80 and -0.82, is hard to evaluate which is the most suited to spatially describe the eruption. Both thresholds are visibly better than the other two, but where -0.80 tends to identify fewer true positives than -0.82, it also detects fewer false positives.

It is important to note that, in the comparison between a MODIS image and a Copernicus vectorial contour, not all pixels not identified as hot spots that overlay the shape are considered false negatives. This is due to the fact the vectorial contours consist of the cumulative lava flows until that contour date. Therefore, in order to assess the active area of the vectorial contour (area where is likely to exist lava flow), the contour of a given day is compared to the previous contour to verify the locations where both are different and speculate on lava flow direction from the vent (example, figure 8).

Figure 8 – Copernicus' shape for 12/12/2014 (a)) and 23/12/2014 (b)) and indication of lava shape changes between the two days

As for the enormous amount of wrongly identified pixels by all thresholds in figure 6, it is believed that the release of gases and the intense heat from "fresh" lava (being the 2nd day of the eruption) can, in part, explain it.

Lastly, what can be stated about the spatial analysis of the method is that the -0.80 and the -0.82 are the best thresholds and the choice of either depends on what is considered to be more relevant: either the detection of the maximum of true positives, or the existence of fewer false positives. The spatial analysis is considered a fine tool to predict the direction of lava flows during the acquisition of two high spatial resolution images, but should not be seen as a replacement for this type of study, since the 1 km pixel size of MODIS imagery is not the most adequate for spatially detailed studies.

4.3 Context analysis

The last analysis performed aimed at validating the previous two analysis and thresholds, by using the same approach on non-eruptive periods, both closer and further apart from the 2014-2015 eruption. Besides that objective, it also gets an insight of the thermal behavior of the island, right before and right after the event.

Firstly, MODIS images were retrieved for days far apart from the eruption, both before and after, and the NTI was calculated, as exemplified in figure 9.

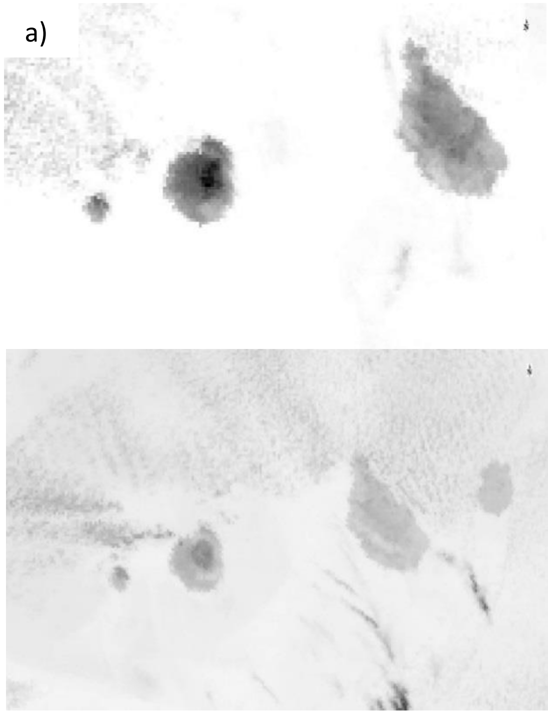

Figure 9 - NTI of MODIS image taken: (a) on 06/02/2014; b) 09/10/2016

It is noticeable in both figures, 9 a) and 9 b), that the caldera is the darker zone of the entire island, meaning that in normal situations it is the coldest. Thus, it seems valid to assume that any of the thresholds used are adequate, since the method does not produce a single false detection for non-eruptive dates far apart from the event.

The images of the eve of the beginning of the eruption (22/11/2014) and the day after its end (09/02/2015) were selected and their NTI calculated, whose results are shown on figures 10 a) and 10 b).

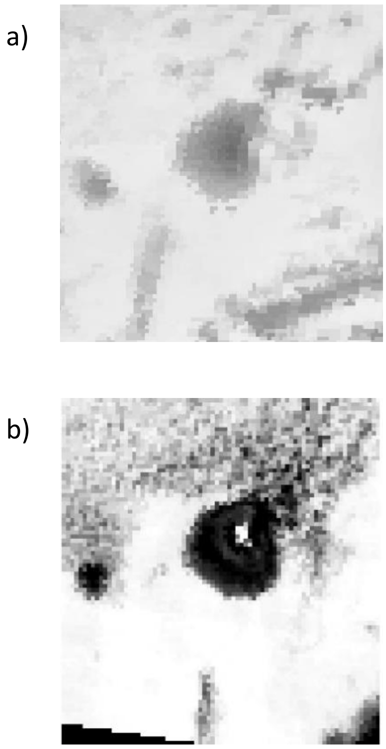

Figure 10 - NTI of MODIS image taken on 22/11/2014; b) NTI of MODIS image taken on 09/02/2015

For the image of 22/11/2014 (figure 10 a)), there are no thermal evidences of the eruption to come. This is supported by the fast lava ascension characteristic to the islands volcanic activity and its small residence time at crustal levels [10]. Concerning the day after the end of the event (figure 10 b)), the caldera is still warmer than the rest of the island. Taking this into consideration, the thresholds used in previous analysis were also tested, but producing no detections. For a pixel to be detected as hot spot, it would require the use of -0.87 as the threshold, producing 3 identifications (figure 11).

In order to better understand the cooling process of the caldera, MODIS images were acquired until the caldera did not show signs of being hotter than their surroundings (figure 12).

As shown on figure 12, the caldera takes less than a month to cool down.

The results of the context analysis support the reliability of the method used and all its thresholds.

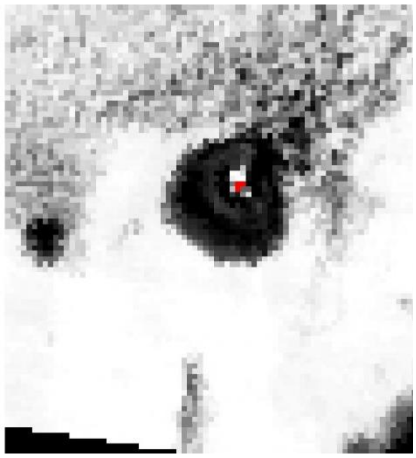

Figure 11 - NTI of MODIS image taken on 09/02/2015 when applied the -0.87 threshold

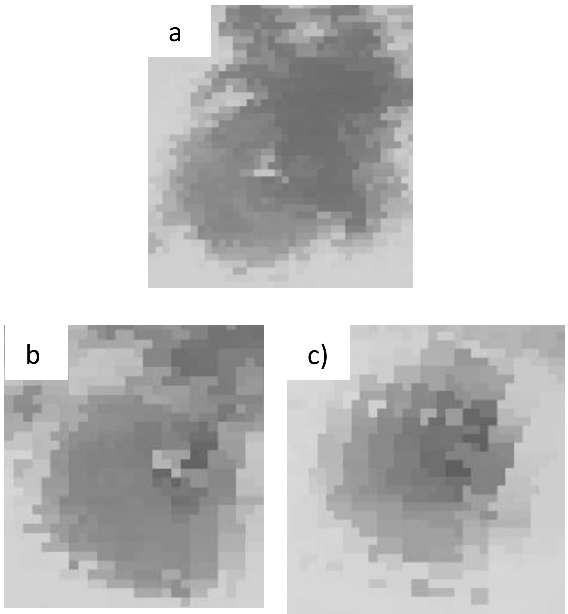

Figure 12 –NTI of MODIS images taken on: (a) 19/02/2015; b) 26/02/2015; c) 05/03/2015;

5. Conclusions

The 2014-2015 Fogo island eruption served as a base to develop and test a methodology for detecting volcanic hot spots, based on the fixed threshold algorithms, namely MODVOLC.

To assess the performance of the method, the capability of describing the volcanic activity throughout the eruption period (temporal analysis), the spatial precision on flagged pixels location (spatial analysis) and the reliability on non-eruptive periods (context analysis) was studied.

The temporal analysis proved to produce a good correlation between the number of identified pixels and the average lava volume flow rate. The best threshold according to this analysis is equal to -0.82, producing a correlation of 0.6971.

The spatial analysis proved to be useful to predict the lava flow direction and position during the interval of two higher spatial resolution images, not replacing, however, the necessity of studying the last, due to MODIS imagery low spatial resolution (1 km). The best thresholds according to this analysis are -0.80 and -0.82, being the ones that achieve a better balance between identifying true hot spots and not producing too many false pixels.

The context analysis proves the method reliable since it does not produce any false detections in non-eruptive days, even those close to the event timeline. It was also possible to roughly estimate that the cooling time of the caldera after the eruption is less than one month.

In summary, it is considered that the method produces valuable data through thermal remote sensing methods that should be taken into consideration as support to the already existing procedures. The main benefit of the method is its ability of reconstructing the event almost on a daily basis. The best threshold to describe the regional reality of this eruption is equal the -0.82 since it clearly produces better results in describing the volcanic activity during the course of the eruption.

In future studies, it would be interesting to apply this methodology to other eruptions, adapting it to the regional reality of the volcano and, if possible, using it to monitor the event, rather than reconstructing it.

6. References

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