Volcanic Hot-Spot detection using SENTINEL-2: results from the comparison with MODIS-MIROVA thermal signals.

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Satellite thermal remote sensing is an effective technique increasingly used for volcanological studies and monitoring. Different thermal detection algorithms and applications using InfraRed region (IR; 0.7–20 m) analysis, are nowadays available, each one with its own advantages and drawback. The differences are due to variabilities in spatial resolution, temporal resolution, spectral resolution of the different satellite sensors used.
The thermal signature (i.e., intensity, dimension, spatial distribution and temporal persistency) of volcanic phenomena may vary in space and time. Different kinds of volcanic activities could be expressed by a spectrum of thermal signals: some more explicit, such as a fresh lava body, others more cryptic, such as a highly viscous lava dome or a hot-degassing surface.

The interpretation of the thermal signature is a challenge, particularly for volcano monitoring and real-time assessment of hazardous scenarios.

**MODIS - Middle InfraRed (MIR) analysis.**
Sensor Pixel width of 1x1 km.

**SENTINEL 2 - Short Wave InfraRed (SWIR) analysis.**
MSI sensor Pixel width of 20x20 meters.
**Spatial resolution 20 meters**  
One overpass each 5 to 2/3 days  
**Dataset since 2015/2017**  
Sensitive to very hot targets

**Short Wave InfraRed region (0.8-2.2 µm)**

**SENTINEL-2 are still under-investigated for volcanological thermal studies.**

Some relevant SWIR fires-devoted hot-spot-detection algorithms using LANDSAT-8 and SENTINEL-2 (Murphy et al., 2016) NHI algorithm by Marchese et al., 2019 to map volcanic hot spots, using SENTINEL-2 and LANDSAT-8 (NHI tool, Genzano EGU pres.).

**At the moment, no operationally systems use these existing high-resolution SWIR-based algorithms for volcanic monitoring tasks and no multi-years and continuous comparison with other automated and web-based hot-spot volcanic detection systems have been still carried out.**
THERMAL HOTSPOTS DETECTION ALGORITHM

Bands: ρ8a (865 nm) - ρ11 (1610 nm) - ρ12 (2190 nm)

Developed for a global thermal volcano monitoring

lava flows, lava lake and lava fields
extrusion phases of lava domes, fumarolic activity,
hot degassing
thermal activity at multiple active craters

ALGORITHM DIVIDED IN 3 STEPS

1) fixed reflectances ratios (implemented by Murphy et al., 2016) are used to identify possible hot pixels “alerted”

2) Thermal Index (TI) = ρ8a + ρ11 + ρ12 for each alerted pixel clusters.

3) Spatial and Statistical analysis of TI, applied to each cluster.

ALERT scanning to define CLUSTER of alerted pixels

- Thermal Index (TI) = ρ8a + ρ11 + ρ12

IF AREA > 9 Pixels
  IF $T_{I_{\text{flex}}}$ < $T_{I_{\text{mean}}}$
    $T_{I_{\text{thresh}}} = T_{I_{\text{flex}}}$
    Pixel Hot > $T_{I_{\text{FLEX}}}$ of pixel in the cluster
  IF $T_{I_{\text{flex}}} > T_{I_{\text{mean}}}$
    $T_{I_{\text{thresh}}} = T_{I_{\text{100%}}}$
    Pixel Hot > 30% of pixel in the cluster

IF number of Pixel(s) alerted > 0
  ALERT binary matrix with Pixel(s) alerted = 1

NO ALERT(S) DETECTED

Massimetti et al., 2020
The algorithm works on a variety of volcanic activity (hot fumaroles, lava domes, lava flows and lava lake, etc.). High sensitivity to low, small thermal anomalies, useful to detect precursor signals and weak hot spots. The spatial/statistical filters allowed to exclude non-volcanic hot-spot (i.e., clouds coverage) or triggered by instrument effects (i.e., diffraction spikes). Compared to the Hotmap algorithm (Murphy et al., 2016), this enhancement is relevant for automated monitoring applications.

Small hot fumaroles (< 9 Pixels) detected on Chaitén volcano.

Comparison between Hotmap and the S2 Algorithm here presented. The new hotspot pixels are constrained in the Stromboli crater terrace area and not outside.
ALGORITHM PERFORMANCE
The reliability of the algorithm was tested on different volcanoes by comparing the number of hot pixels detected with MODIS-derived radiant-heat-flux timeseries processed by the MIROVA system (http://www.mirovaweb.it/).

Eight volcanoes case studies from January 2016 to October 2019, characterized by four end-members volcanic heat sources: lava flows, lava lake, lava domes and open-vents.

**MIROVA Middle Infrared Observations of Volcanic Activity**
MODIS sensor on Aqua & Terra satellites
- Spatial resolution 1 km
- 4 overpasses per day
- 1-4 hours from real-time
- Dataset available since 2000
- MIR radiance analysis 3.9 µm

\[ \text{VRP} = 18.9 \times 10^6 \times \sum_l L_{\text{MIR,hot}} - L_{\text{MIR,Bk}} \]

*Coppola et al., 2016*

**SENTINEL 2 MSI – Algorithm >**
Number of Hot Pixels detected (S2Pix, nb.)
\[ \approx \text{hot area exposed at magmatic temperatures (ca. 500–1400 K)} \]

**MODIS – Mirova >**
Volcanic Radiative Power (VRP, in Watt)
radiated from surfaces with T > 500 K
**Lava Flows**

S2Pix VRP 2016 – 2019 timeseries

**Etna (Sicily Island, Italy)**

Correspondence in S2Pix/VRP, both during “low thermal regime”, (strombolian and degassing activity VRP < 10^8 W and S2Pix < 100) and “high thermal regime” (sustained strombolian activity or lava effusion VRP > 10^8 W and S2Pix > 100, yellow fields).

**Klyuchevskoy (Kamchatka, Russia)**

Good S2Pix/VRP correlation, main thermal activity was recorded between March - November 2016, during lava effusion period (max VRP > 10^9 W, S2Pix >1000). A sharp drop in the thermal activity marked the end of the eruptive phase on November 2016.
LAVA LAKES  S2Pix VRP 2016 – 2019 timeseries

Erta Ale (Afar region, Ethiopia)
Consistency between MIROVA and S2 trends is remarkable both during the lava-lake activity (before January 2017, S2Pix < 100 and VRP < 10^8 W), as well as during the lava flows’ production (after January 2017; S2max > 1000 pix. and VRP > 10^9 W).

Masaya (Nicaragua)
Persistent thermal output detected by MIROVA since the lava lake resumption in December 2015. S2Pix (10 to 200 pixels) maintains a good overall match with VRP (10^7–10^8 W). Anyway, the S2 hot spots appear more scattered: i) clouds influence; (ii) inner variability in thermal emission of Masaya lava-lake system.
Stromboli (Sicily, Italy)
Persistent thermal anomalies associated to the strombolian activity. The S2Pix/VRP show excellent agreement during effusive activity (yellow fields), threshold of 50 MW or 50 S2Pix, representing the transition between strombolian and effusive regimes. During weak strombolian activity the algorithm is sensitive to very low thermal emissions (S2Pix < 10, no VRP).

Villarrica (Chile)
VRP shows cycles of decreasing and increasing thermal emissions. The S2Pix appears stable with a value around 10 pix. = the area occupied by the thermal anomaly remains roughly constant (i.e., the bottom of the crater), while the thermal flux varies.
Bezymianny (Kamchatka, Russia)
Bezymianny activities consist of fumarolic emissions, lava-dome growth phases, strong explosions and extrusion of viscous lava flows. This variability is represented by VRP, showing a “thermal baseline” (VRP < 10^7 W), and peaks in thermal flux. This activity is tracked also by the S2Pix, with the same overall trend.

Lascar (Chile)
Stable and persistent thermal signal in VRP and S2Pix signals. S2Pix mimics the VRP trend both in the 2016–2017 phase (VRP < 10^7 W and S2Pix < 10), and during phases of increased thermal activity, as occurred from November 2018.
THERMAL BEHAVIOR OF THE VOLCANIC HOT SOURCES

S2Pix vs. VRP plots, dashed lines representing “isotherm” curves.

VRP = radiant flux in Watt / S2Pix = proxy of the hot area - > region of the plot where the data fall is a temperature indicator.

Lava flow
isotherm trend
and linearly
grow in area
and heat flux

Lava lake
Etna: small-size
Erta Ale: anomalies
Masaya: with a low
confined within the
thermal source
hot area and
limited variations in the
heat flux

Lava dome
small-size
anomalies
involved in dome-forming eruptions

Open Vent
Increasing heat flux with stable hot area due to morphological constrain.

Massimetti et al., 2020

Variable relationships between temperature and hot area of volcanic hot emitting body
HIGH-SPATIAL-RESOLUTION SWIR SENSITIVITY.

Improved ability of the algorithm to detect small and low thermal emissions which are undetected by MIROVA (based on MODIS sensor), due to high resolution (20 meters/pixel) of SENTINEL 2 MSI sensor and SWIR sensitivity to magmatic temperatures. This ability is of great interest in order to identify possible thermal precursors at explosive and high-risk volcanoes.

Massimetti et al., 2020

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MONITORING APPLICATIONS and FUTURE PERSPECTIVES

The algorithm presented here runs operationally on the multiplatform MOUNTS volcanic monitoring system online since the beginning of 2018 (http://www.mounts-project.com/home), using the SENTINEL constellation (-1, -2 and -5P) to retrieve and display key parameters volcano monitoring timeseries, such as deformation, heat anomalies and SO2 flux, in near real time.

Future Perspective:
- joining the SENTINEL 2 MSI and MODIS-MIROVA dataset, in order to daily provide a specifically devoted product for the volcanic thermal activity characterization;
- Application on LANDSAT 8 OLI thermal dataset, with 30 m/pixel resolution in the NIR/SWIR bands 7 – 6 – 5.

Modified from Valade et al., 2019
CONCLUSIONS

- a new algorithm for detecting and counting hot thermal anomalies in volcanic environments, with a global applicability, using SENTINEL-2. Based on bands 12, 11 and 8a spectrally, spatially and statistically elaborated with a pixel resolution of 20 meters;
- higher sensitivity of SENTINEL-2 to detect subtle low-temperature thermal emissions, useful to track weak precursor signals;
- S2Pix number compared with VRP by MODIS-Mirova thermal dataset during an almost four-year-long period, at different volcanoes, with results demonstrating a coherent matching;
- Exploring S2Pix/VRP relationships about thermal features related to different volcanic processes;
- SENTINEL-2 thermal signal analysis can enhance the study and monitoring of several volcanic processes.

THANKS!

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REFERENCES: