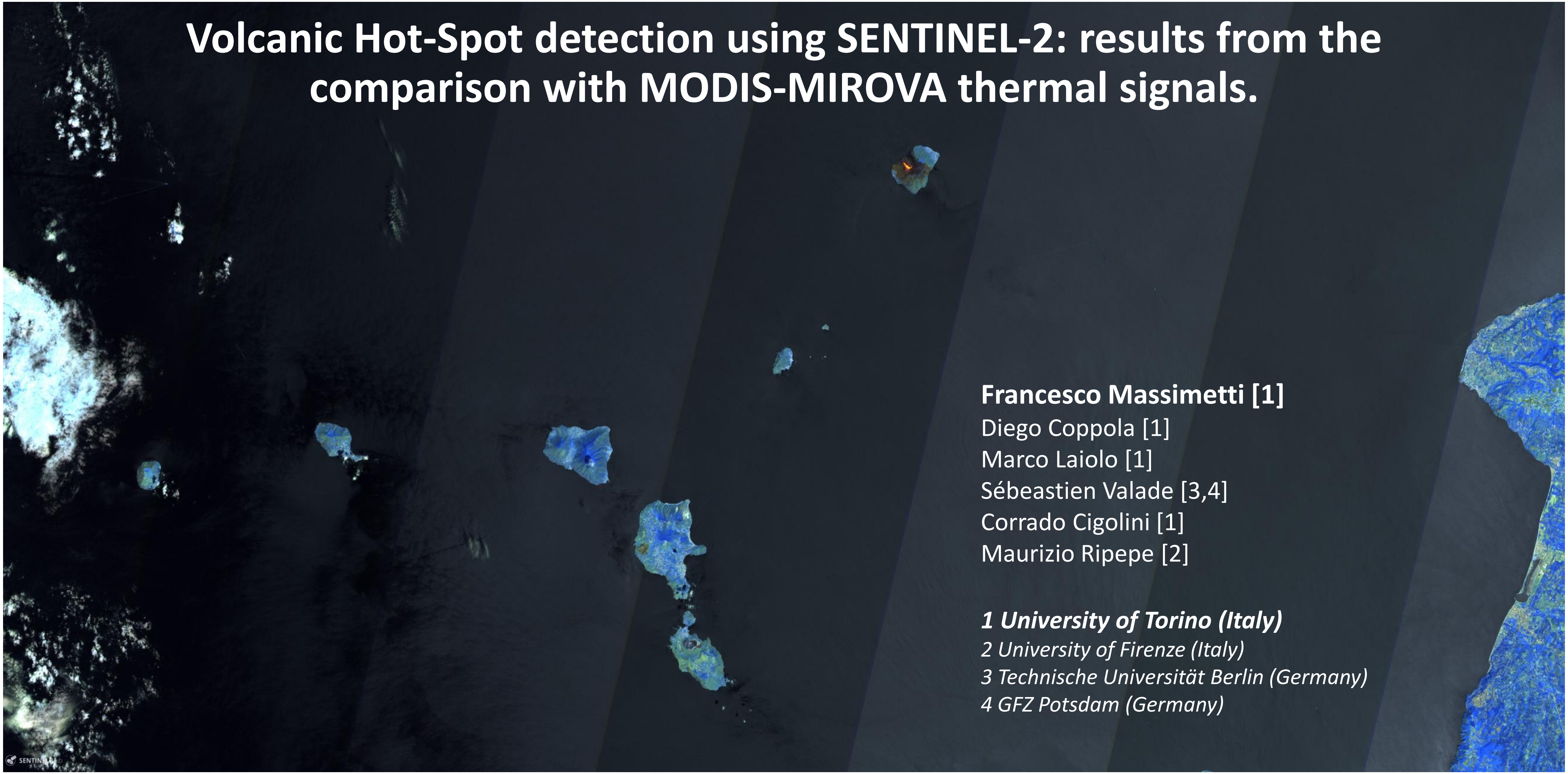
Volcanic Hot-Spot detection using SENTINEL-2: results from the comparison with MODIS-MIROVA thermal signals.



Francesco Massimetti [1]
Diego Coppola [1]
Marco Laiolo [1]
Sébeastien Valade [3,4]
Corrado Cigolini [1]
Maurizio Ripepe [2]

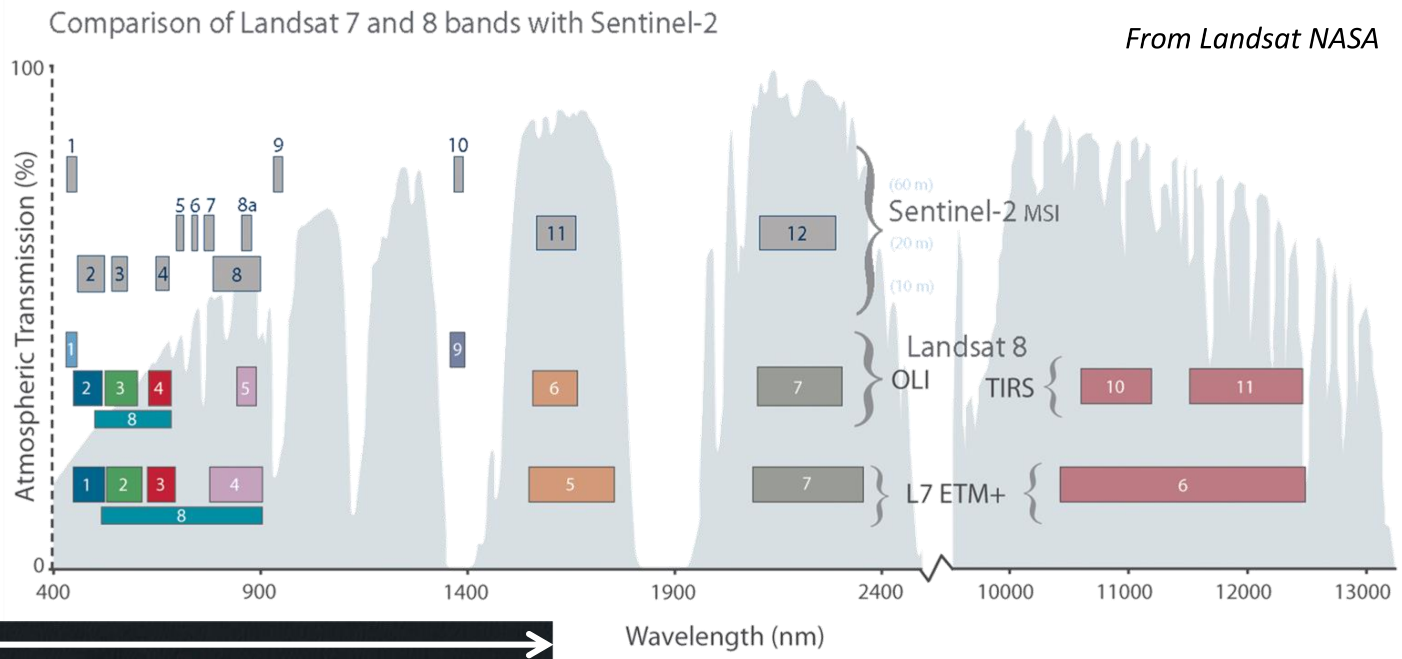
1 University of Torino (Italy)
2 University of Firenze (Italy)
3 Technische Universität Berlin (Germany)
4 GFZ Potsdam (Germany)

EGU General Assembly 2020

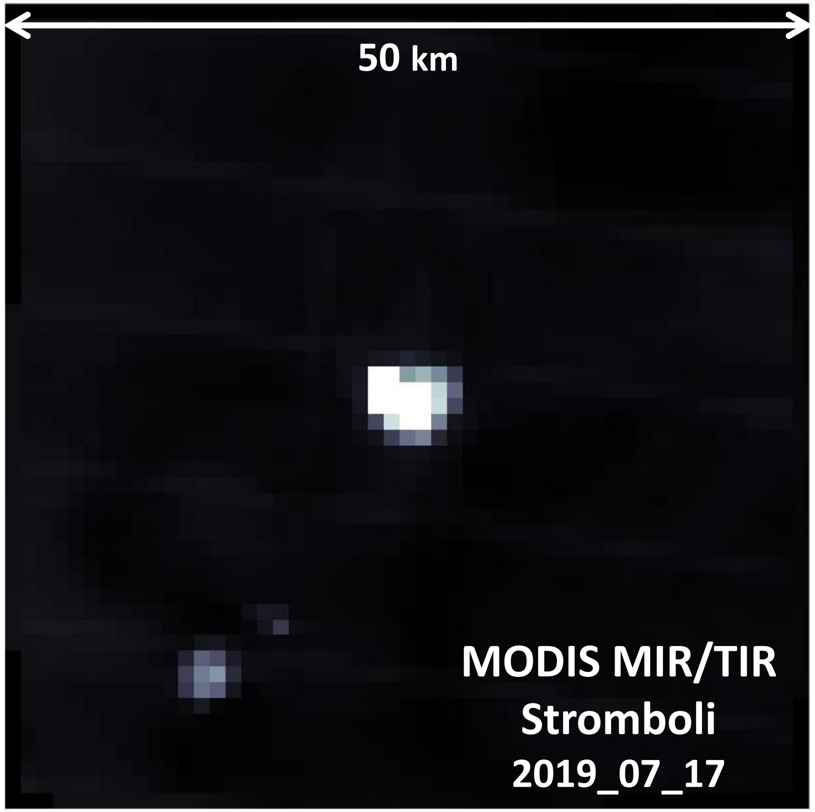
EGU2020: Sharing Geoscience Online
4-8 May 2020

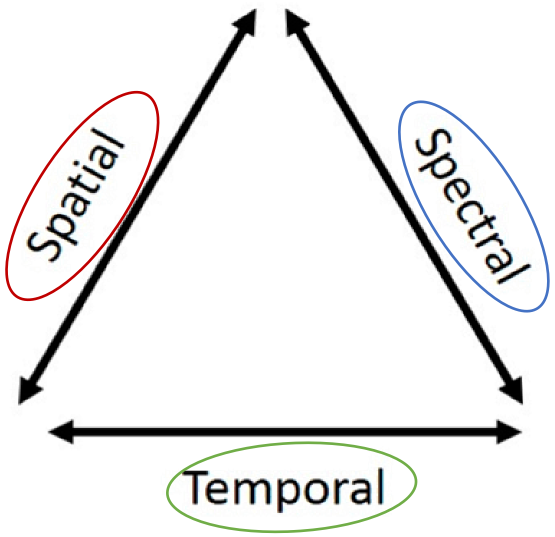
EGU2020-5095
https://doi.org/10.5194/egusphere-egu2020-5095
Session NH6.1, 7 May 2020

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.



From Landsat NASA



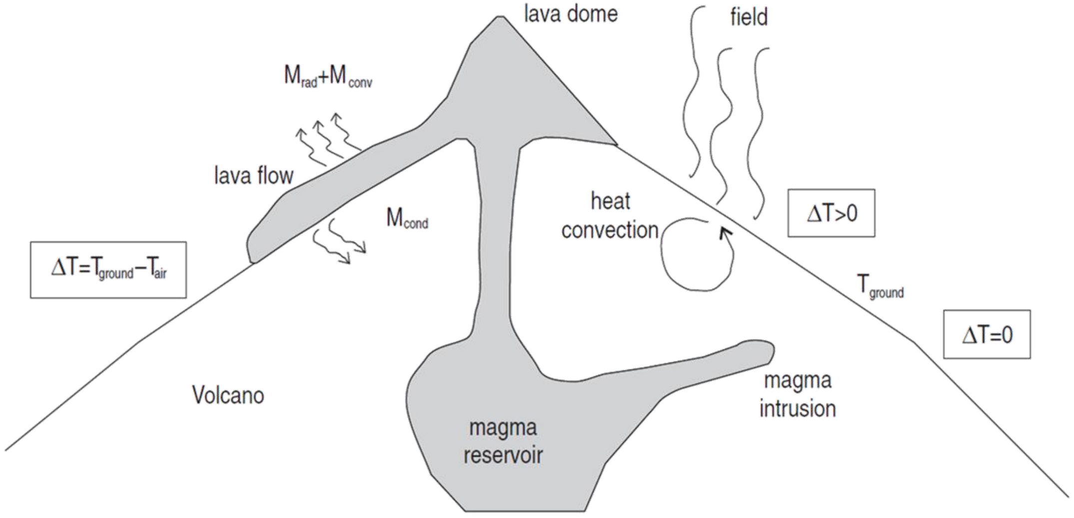


Modified from Blackett, 2017

VOLCANIC THERMAL SIGNATURE

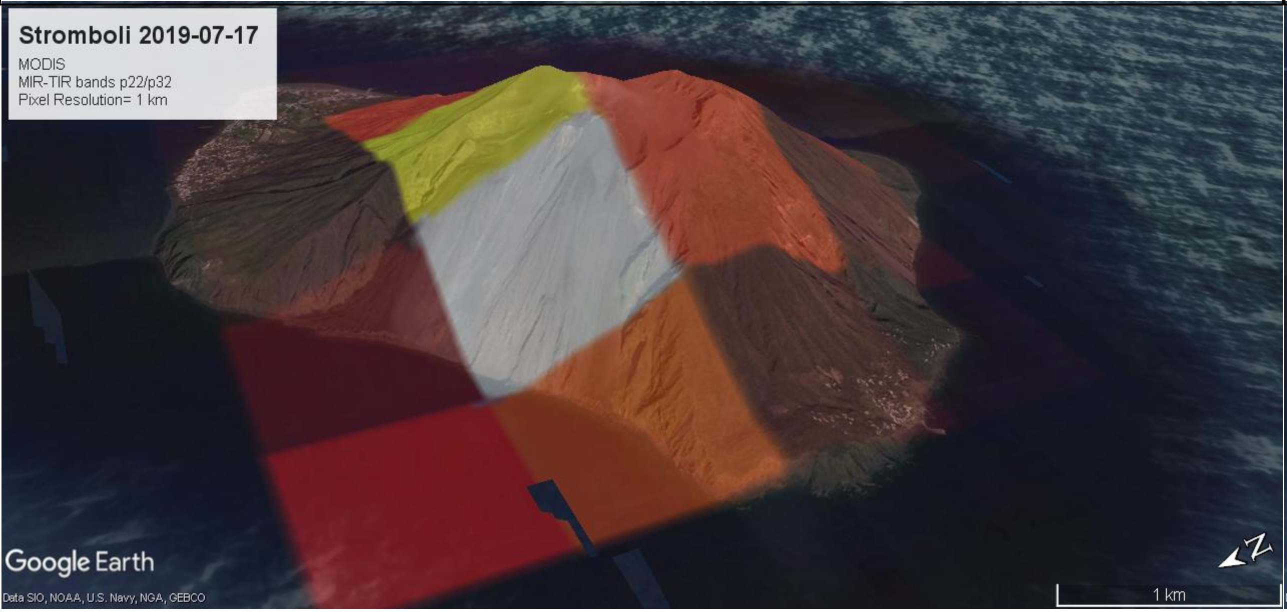
The **thermal signature** (i.e., intensity, dimension, spatial distribution and temporal persistency) of volcanic phenomena may vary in space and time. Different kinds of volcanic activities could be expressed by a spectrum of thermal signals: some more explicit, such as a fresh lava body, others more 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.



From Harris, 2013

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

Nowadays, more advanced monitoring requests

New satellite IR sensors available

limits (spatial/temporal/spectral) of old IR satellite sensor used (MODIS/ASTER, etc).

***SENTINEL-2* satellite** (Copernicus – ESA) **M**ulti**S**pectral **I**nstrument

Sentinel-2A and 2B platform.

Spatial resolution <u>20 meters</u>

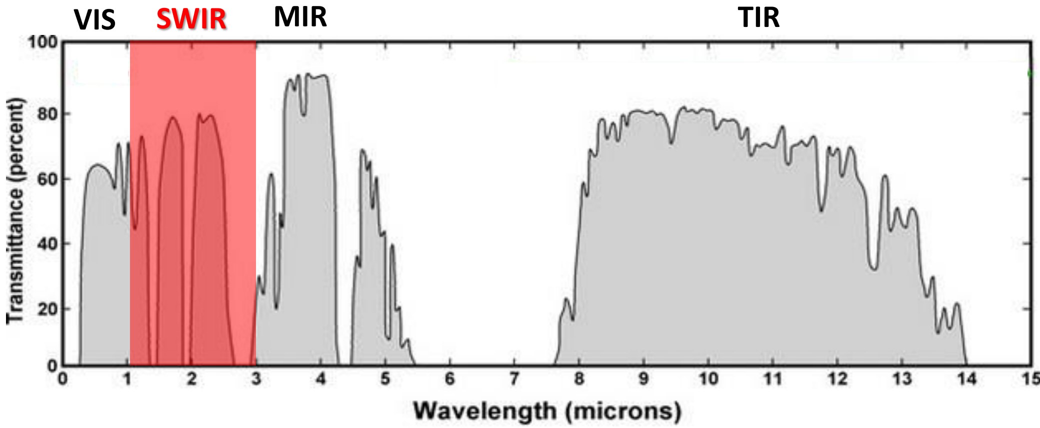
Dataset since 2015/2017

Short Wave InfraRed region (0.8-2.2 µm)

One overpass each 5 to 2/3 days

Sensitive to very hot targets

sentinel-2 esa



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.*).

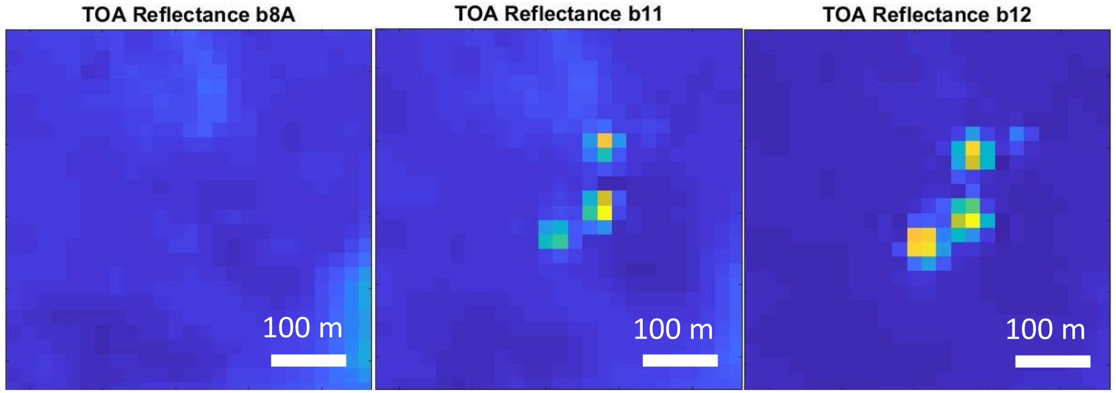
Wavebands of the SENTINEL 2 MSI sensor

Band Number	Resolution (m)	Central Wavelength (µm)	Purpose
Band 1	60	0.443	Aerosol detection
Band 2	10	0.490	Blue
Band 3	10	0.560	Green
Band 4	10	0.665	Red
Band 5	20	0.705	Vegetation classification
Band 6	20	0.740	Vegetation classification
Band 7	20	0.783	Vegetation classification
Band 8	10	0.842	Near Infrared
Band 8a	20	0.865	Vegetation classification (NIR/SWIR)
Band 9	60	0.945	Water vapor
Band 10	60	1.375	SWIR - Cirrus
Band 11	20	1.610	SWIR
Band 12	20	2.190	SWIR

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)



Stromboli Crater Sector
Sentinel 2 Three Bands

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.*

Step 1

Alerted Pixel(s)
Find α, β, S, γ conditions

ALERT binary matrix with Pixel(s) alerted = 1

IF number of Pixel(s) alerted > 0 → **NO ALERT(S) DETECTED**

Step 2

ALERT scanning to define CLUSTER of alerted pixels
-
Thermal Index (TI) = ρ8a + ρ11 + ρ12

Step 3

IF AREA > 9 Pixels → **AREA ≤ 9 Pixels** — **Pixel Hot = α + β + S + γ**

CLUSTER SPATIAL AND STATISTICAL ANALYSIS
TI_{mean}, $TI_{30\%}$, TI_{flex} calculation for each cluster
(each connected component in ALERT)

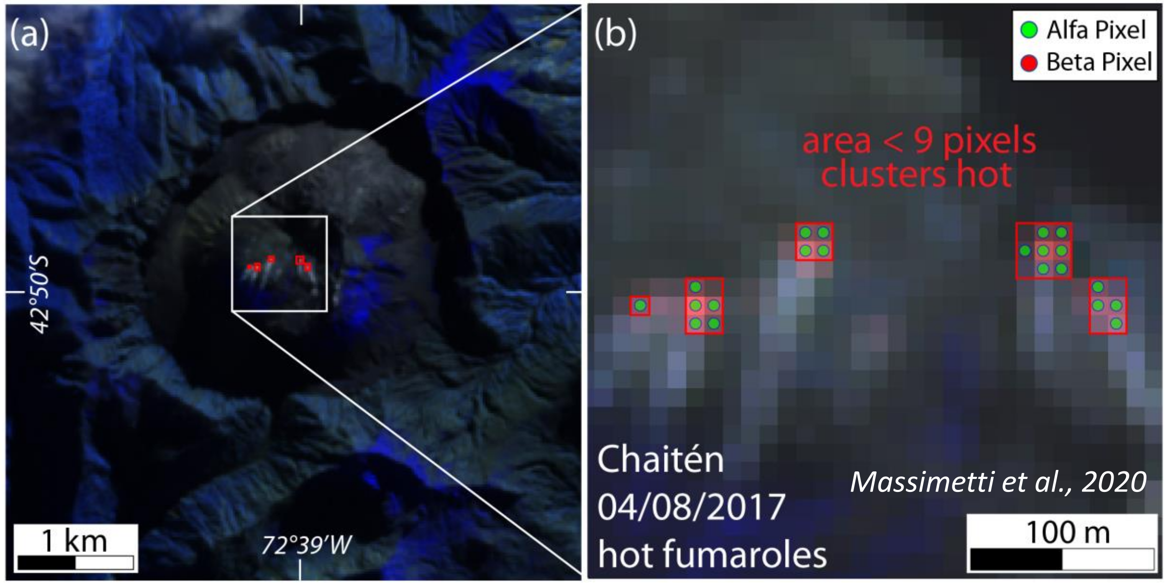
IF $TI_{flex} < TI_{mean}$ → **$TI_{thresh} = TI_{flex}$** — **Pixel Hot > TI_FLEX of pixel in the cluster**

IF $TI_{flex} > TI_{mean}$ → **$TI_{thresh} = TI_{30\%}$** — **Pixel Hot > 30% of pixel in the cluster**

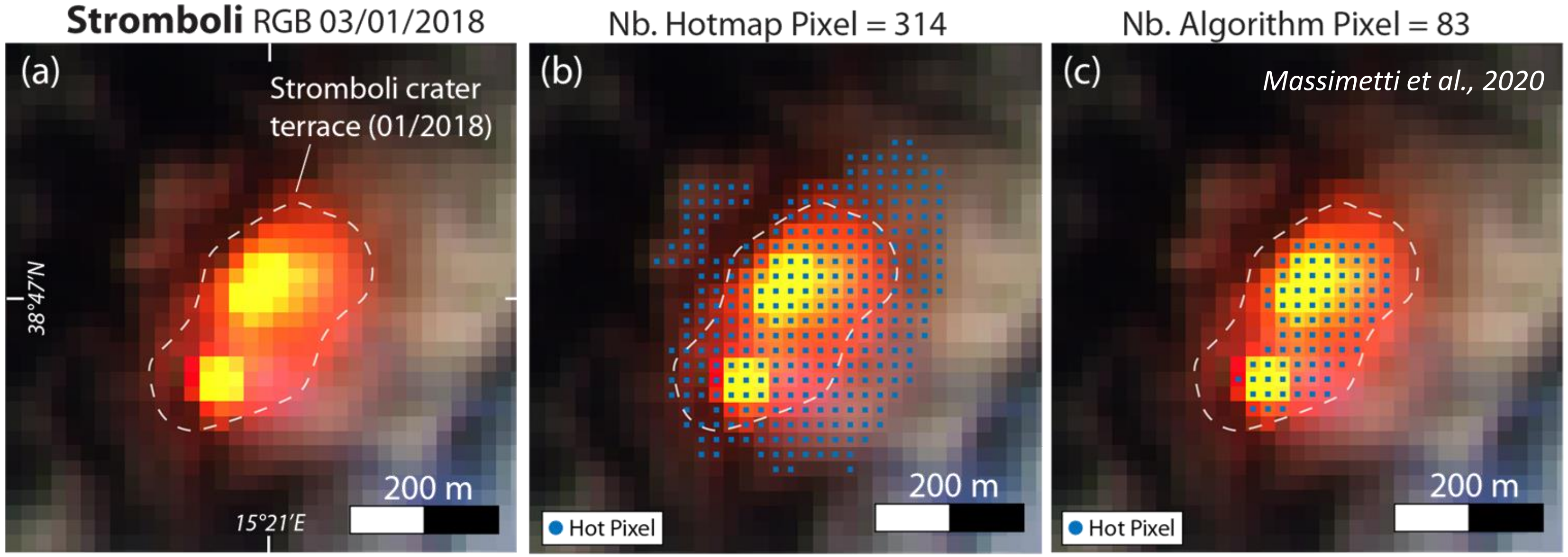
Massimetti et al., 2020

EGU General Assembly 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

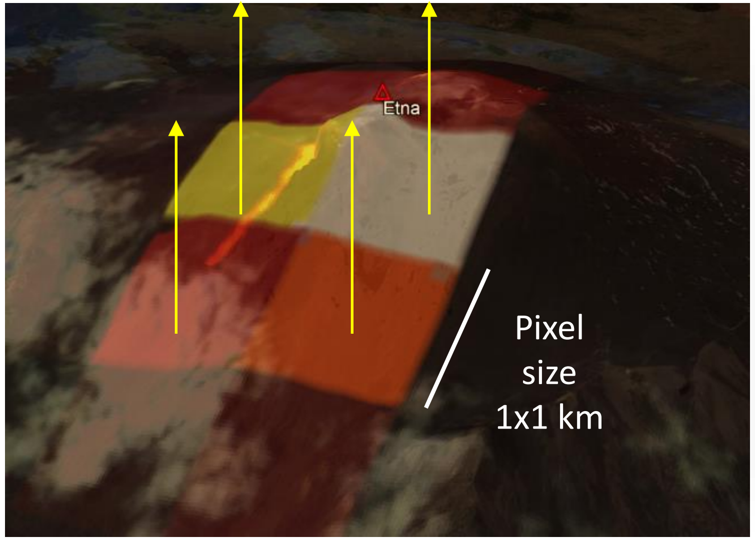
MODIS sensor on Aqua & Terra satellites

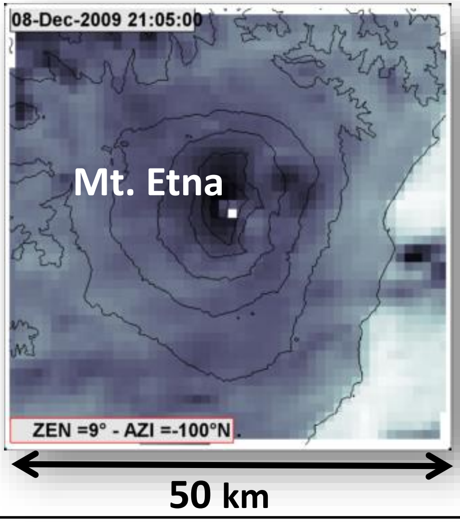
- Spatial resolution 1 km
- 4 overpasses per day
- 1-4 hours from real-time
- Dataset available since 2000
- MIR radiance analysis 3.9 µm

DST Dipartimento di Scienze della Terra

$$VRP = 18.9 \times 10^6 \times \sum_1^n L_{MIR,hot} - L_{MIR,Bk}$$

Coppola et al., 2016





SENTINEL 2 MSI – Algorithm >

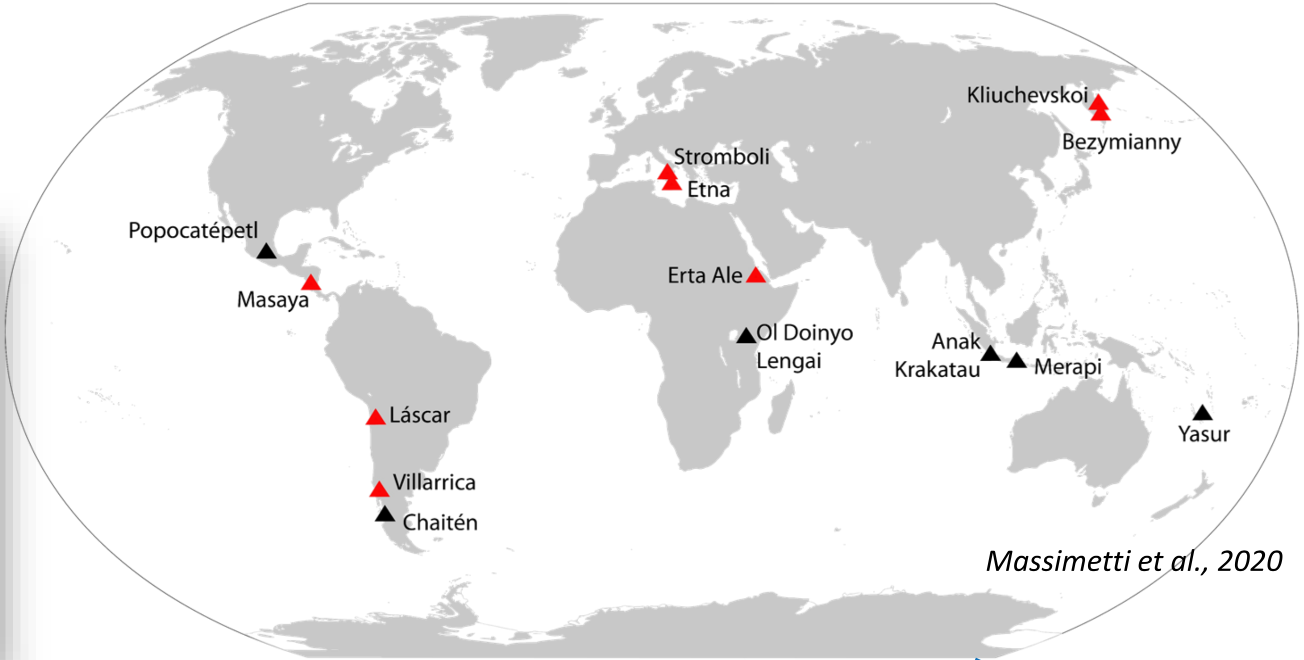
Number of Hot Pixels detected (S2Pix, nb.)

≃ hot area exposed at magmatic temperatures (ca. 500–1400 K)

MODIS – Mirova >

Volcanic Radiative Power (VRP, in Watt)

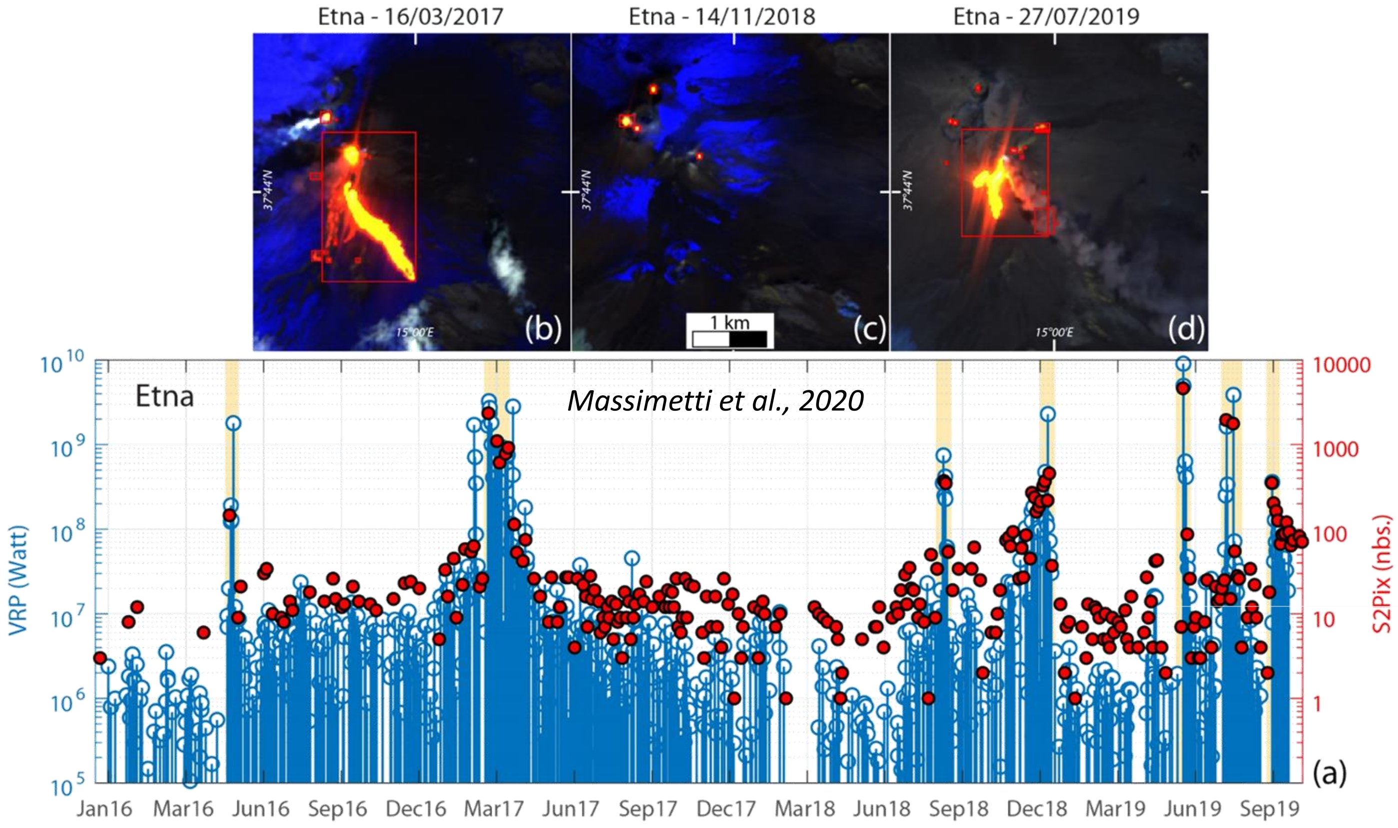
radiated from surfaces with T > 500 K



Massimetti et al., 2020

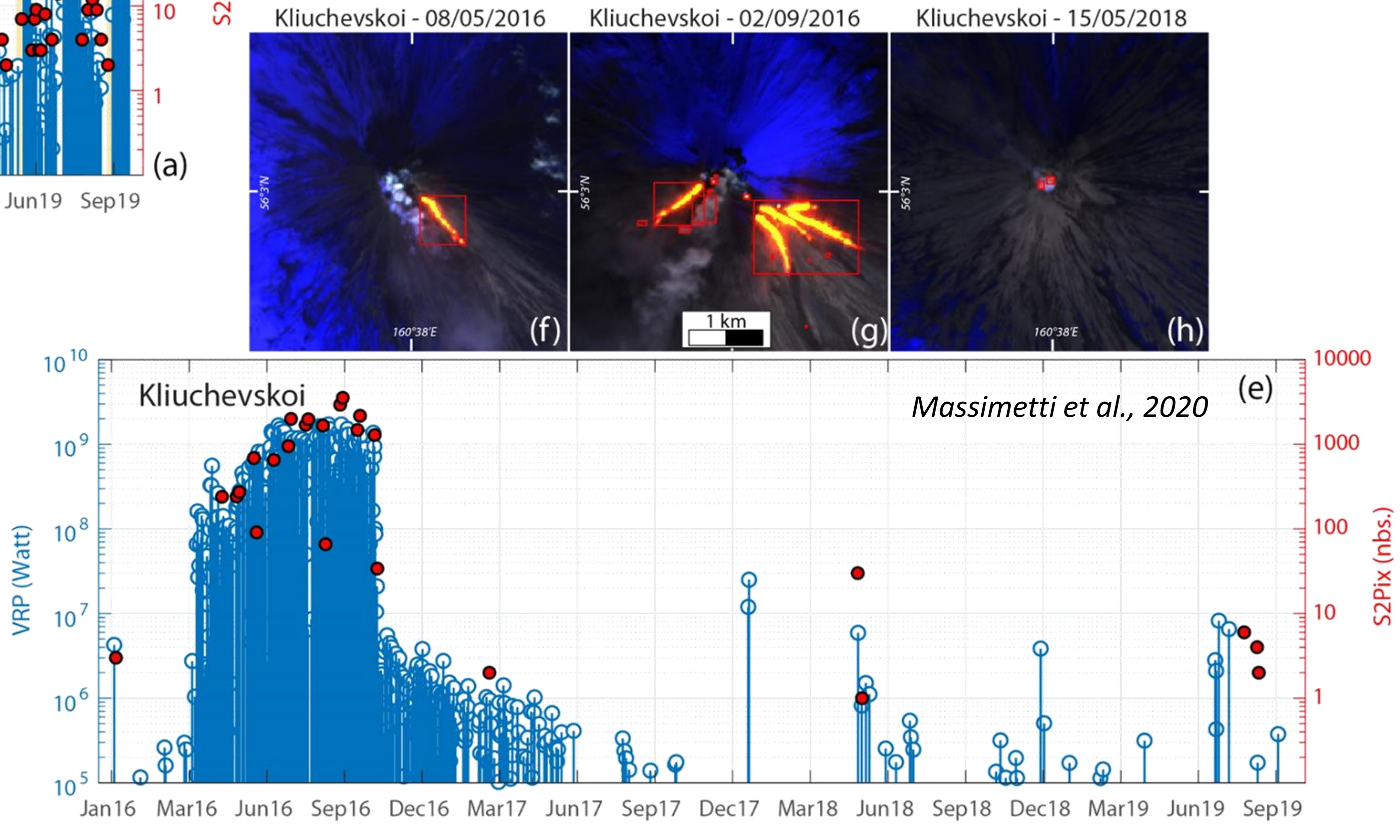
EGU General Assembly 2020

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).

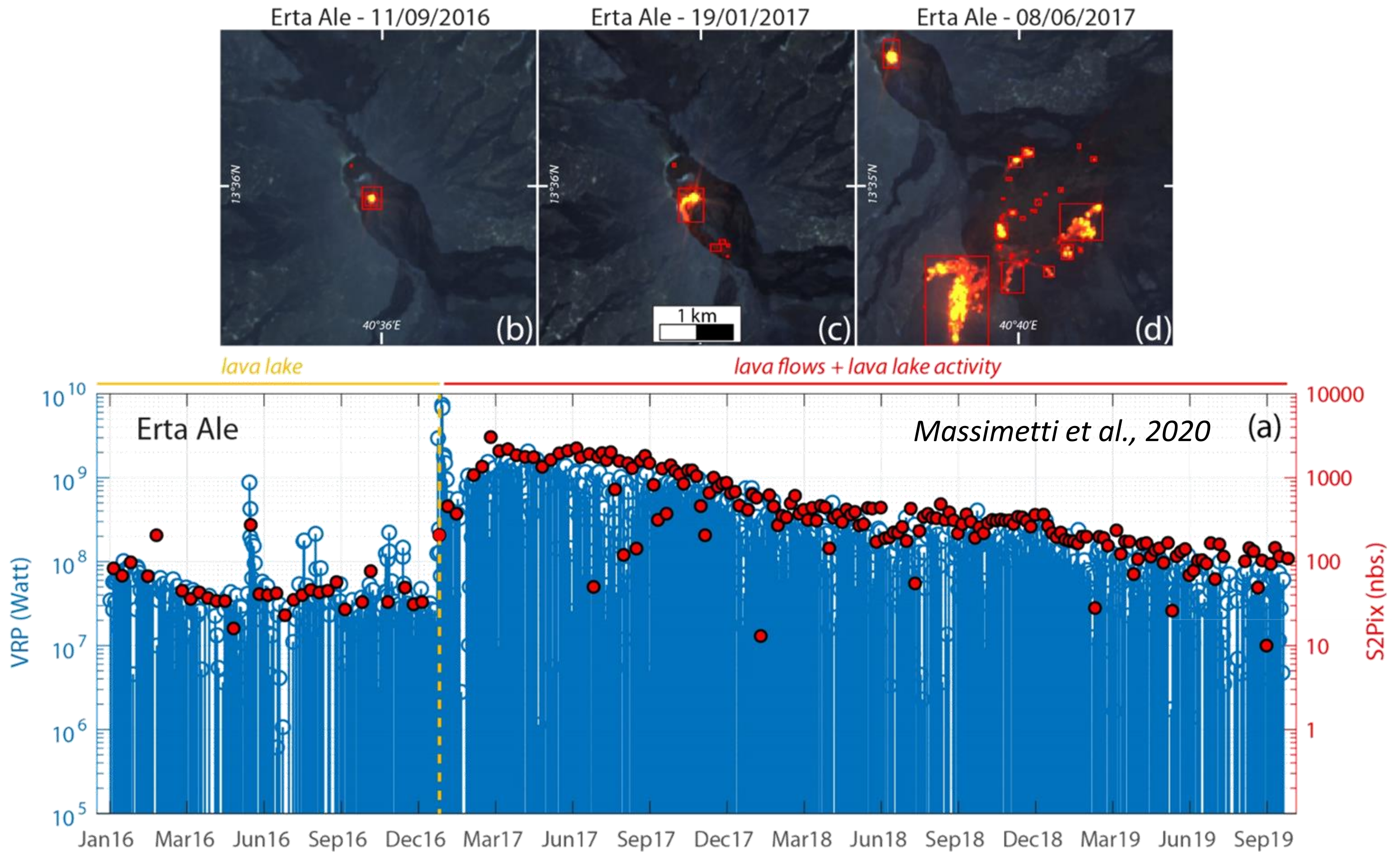


Klyuchevskoy (Kamchatka, Russia)

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.

EGU General Assembly 2020

LAVA LAKES S2Pix VRP 2016 – 2019 timeseries

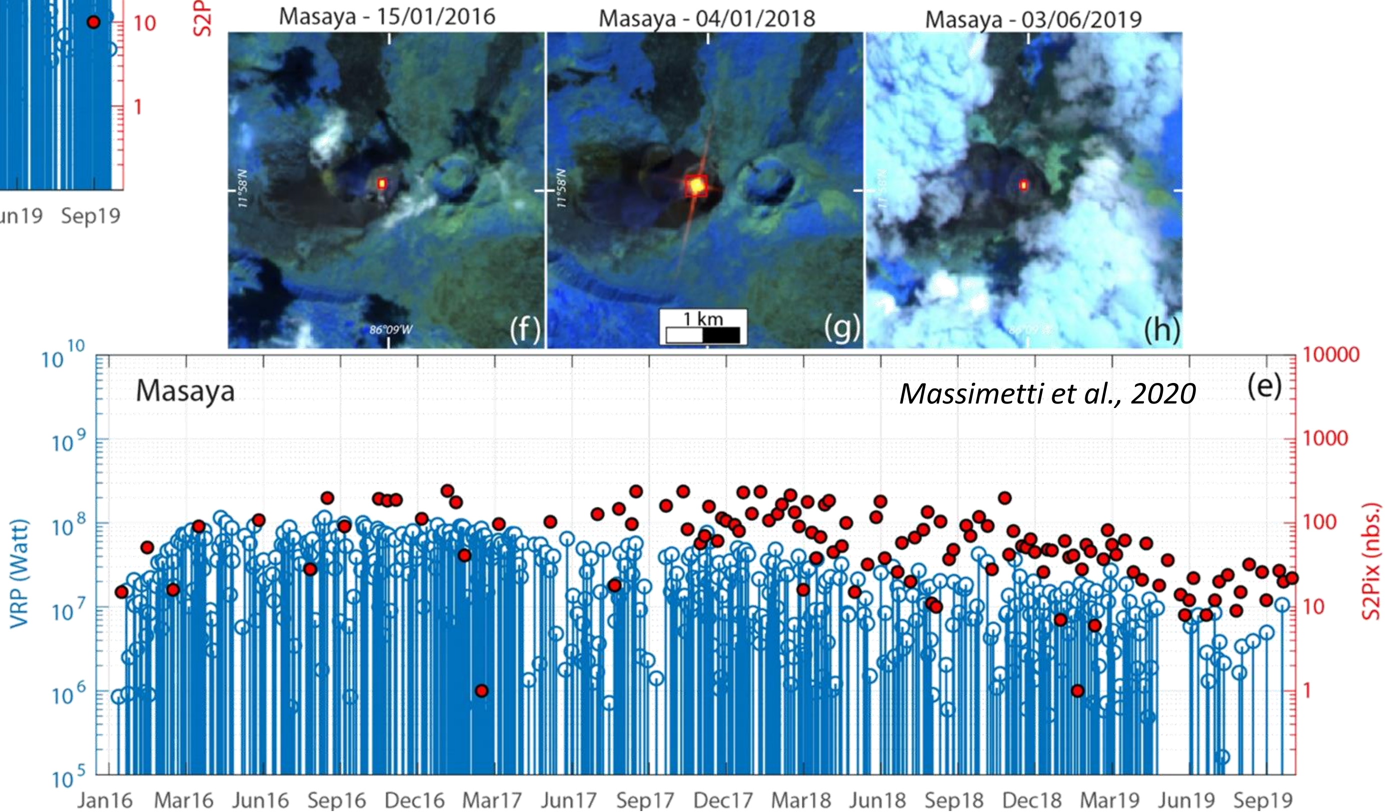


Erta Ale (Afar region, Ethiopia)

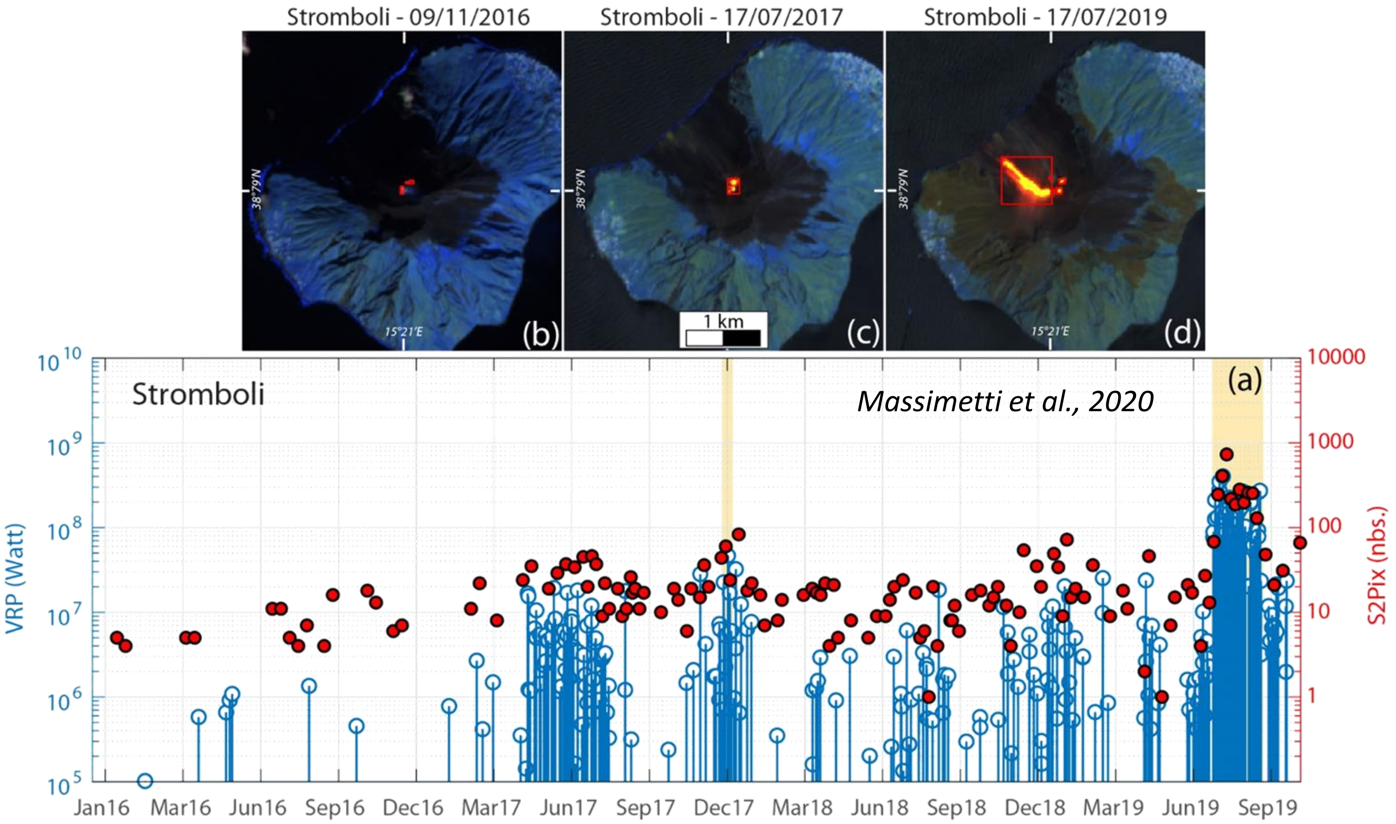
Consistency between MIROVA and S2 trends is remarkable both during the lava-lake activity (before January 2017, S2Pix < 100 and VRP < 10^8 W), as well as during the lava flows' production (after January 2017; S2max > 1000 pix. and VRP > 10^9 W).

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.



OPEN VENTS S2Pix VRP 2016 – 2019 timeseries

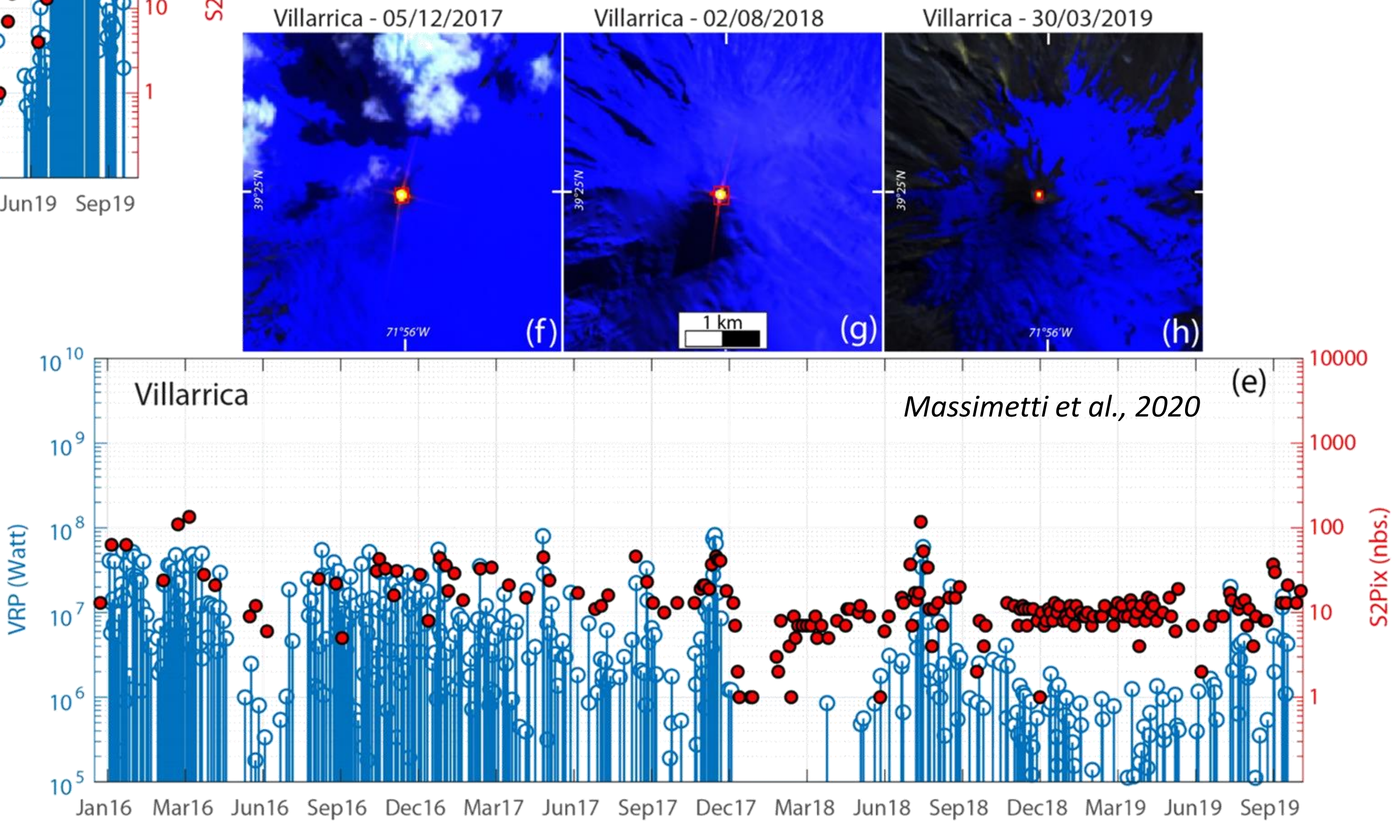


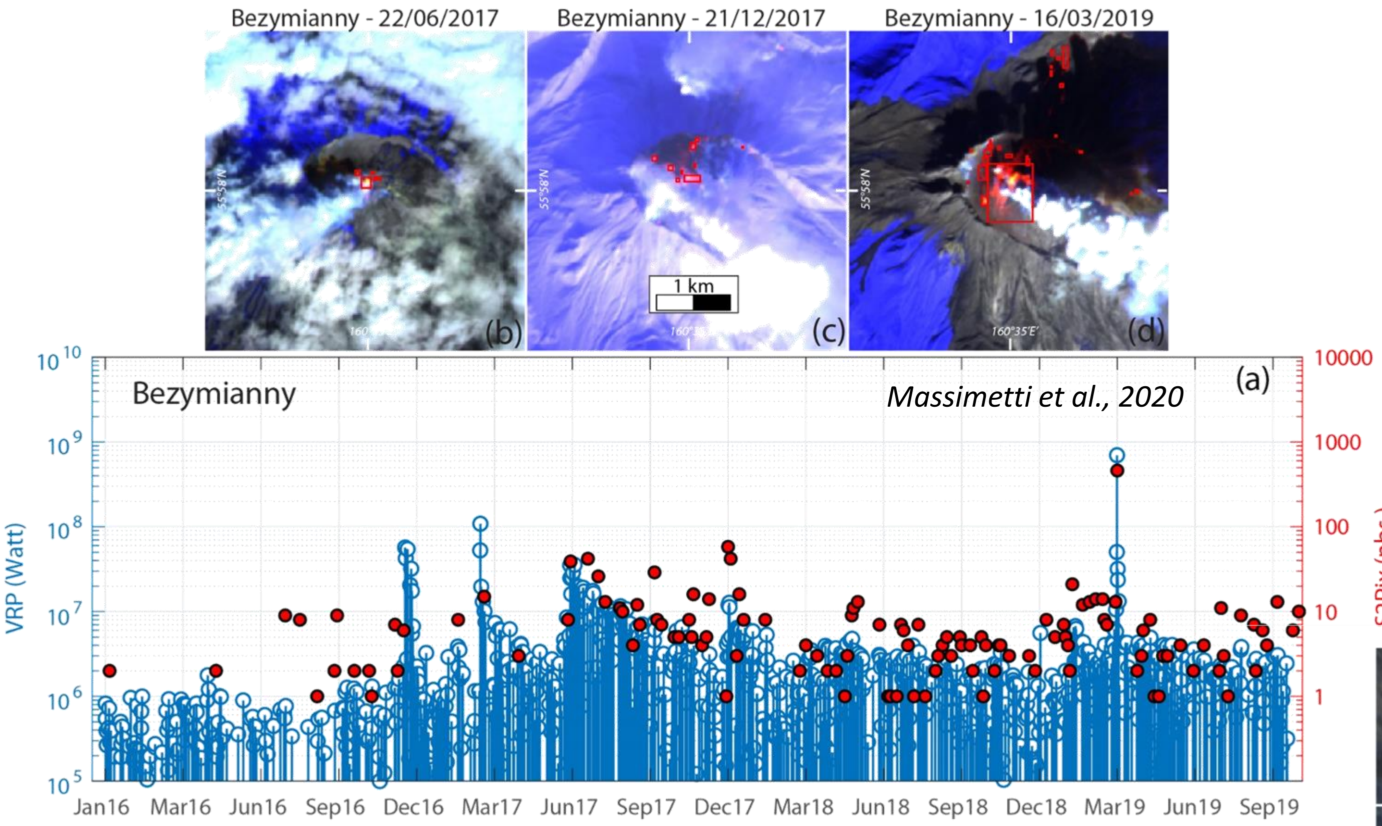
Stromboli (Sicily, Italy)

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.





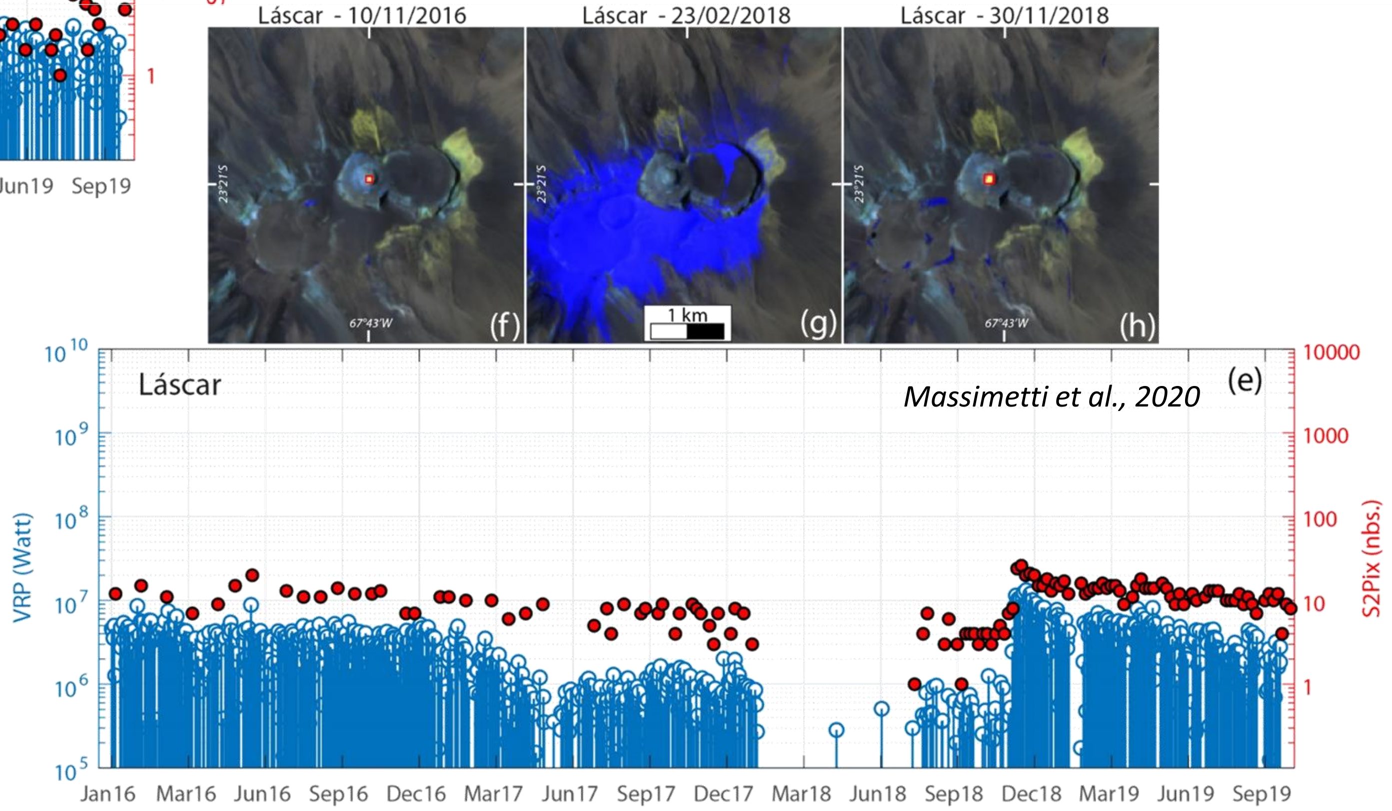
LAVA DOMES S2Pix VRP 2016 – 2019 timeseries

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.



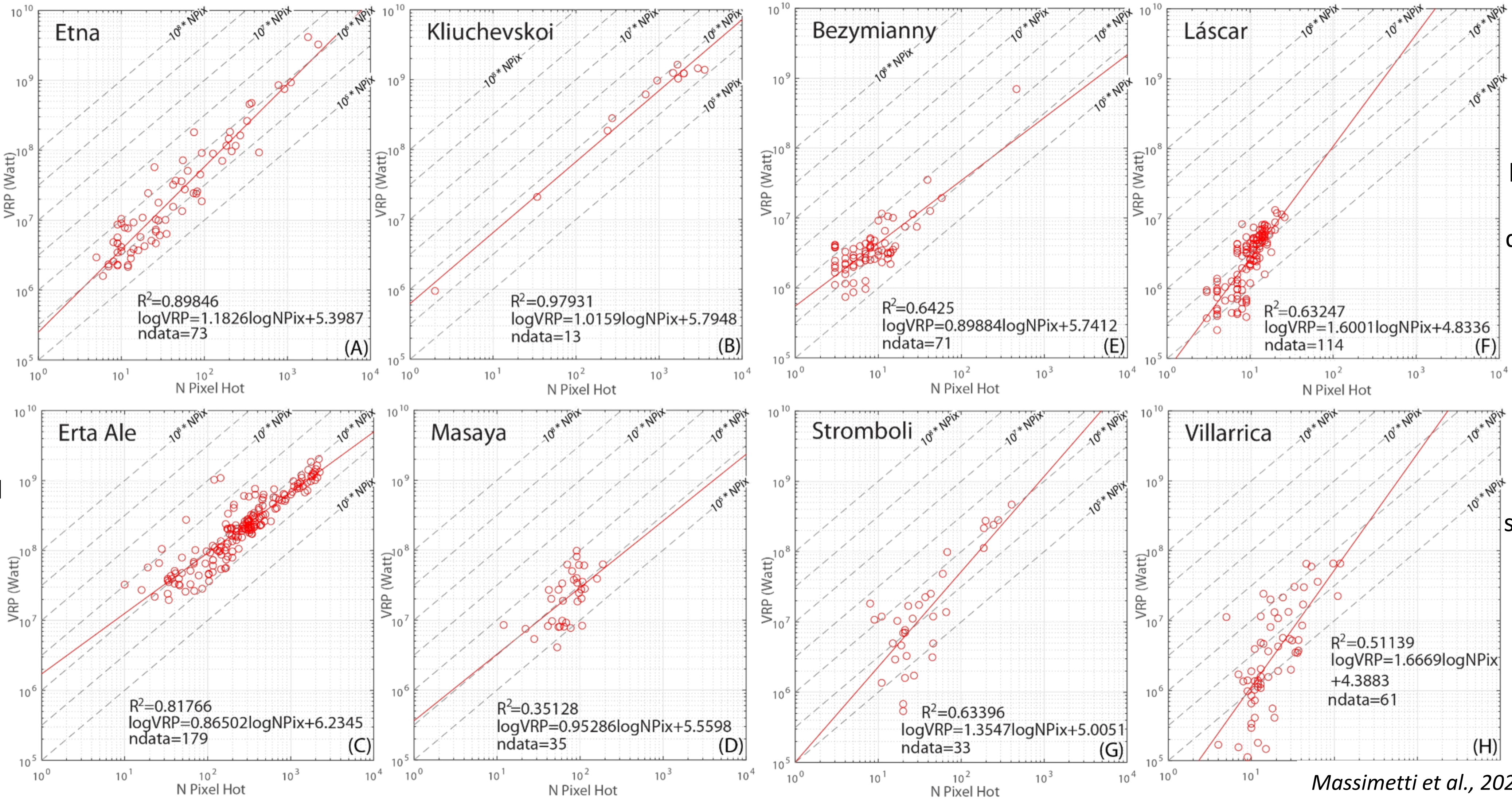
THERMAL BEHAVIOR OF THE VOLCANIC HOT SOURCES

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 dome
small-size anomalies with a low heat radiation involved in dome-forming eruptions



Lava lake
Erta Ale: variable thermal regimes
Masaya: thermal source confined within the crater, limited variations in the hot area and heat flux

Open Vent
Increasing heat flux with stable hot area due to morphological constrain. Increase in source temperature

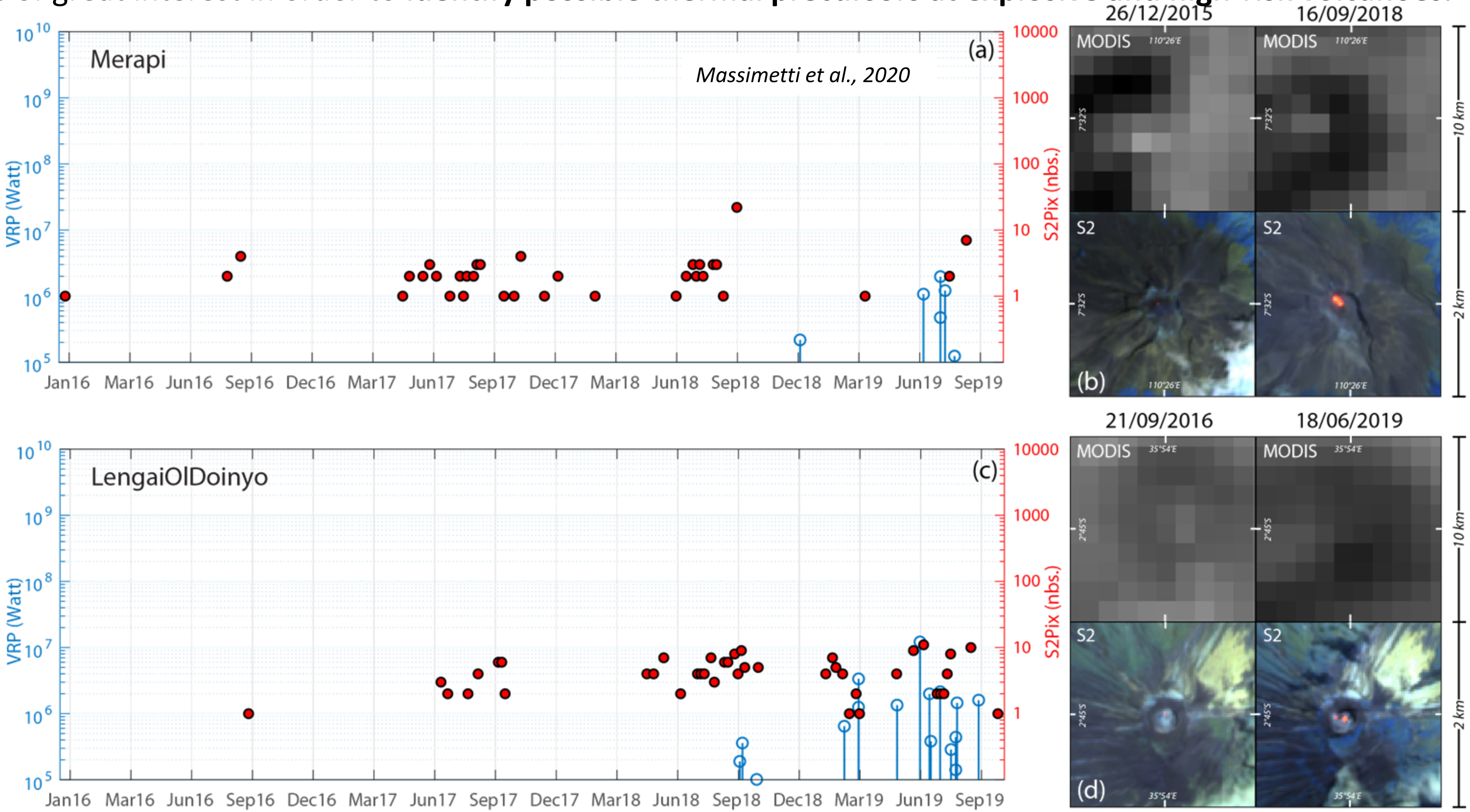
Massimetti et al., 2020

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.**

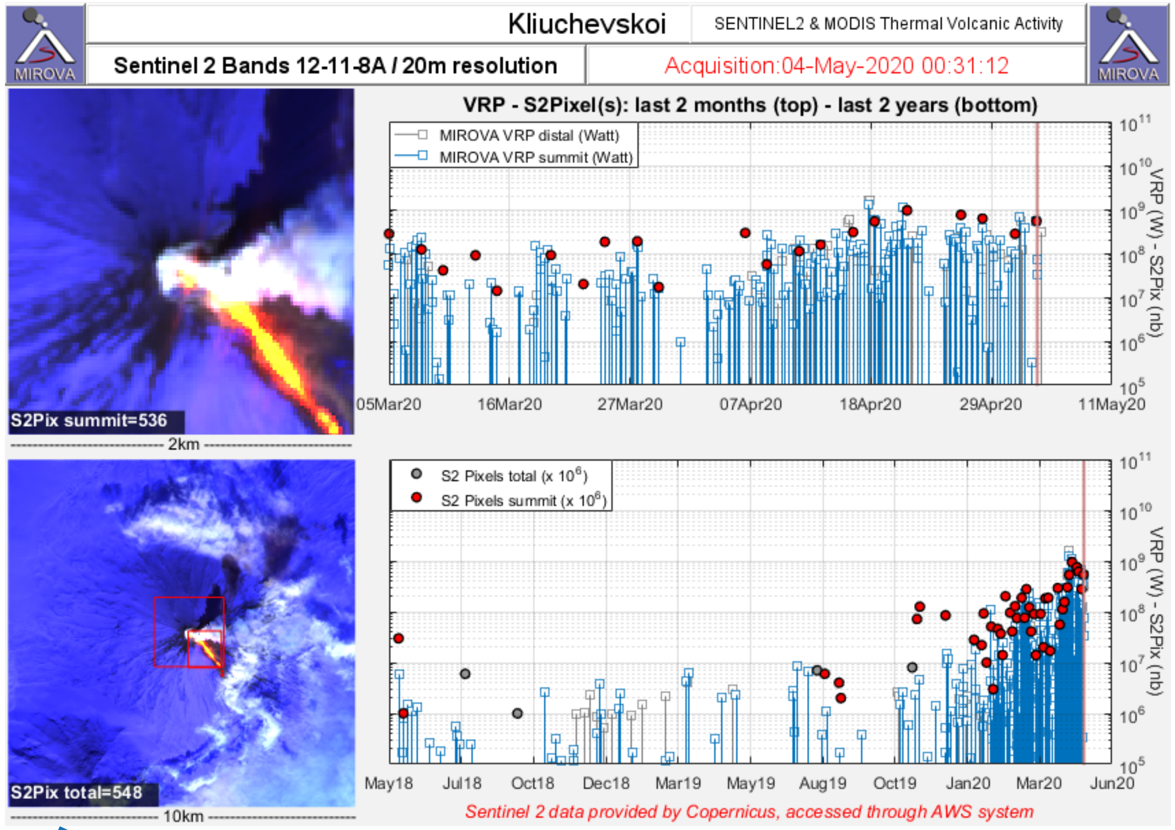


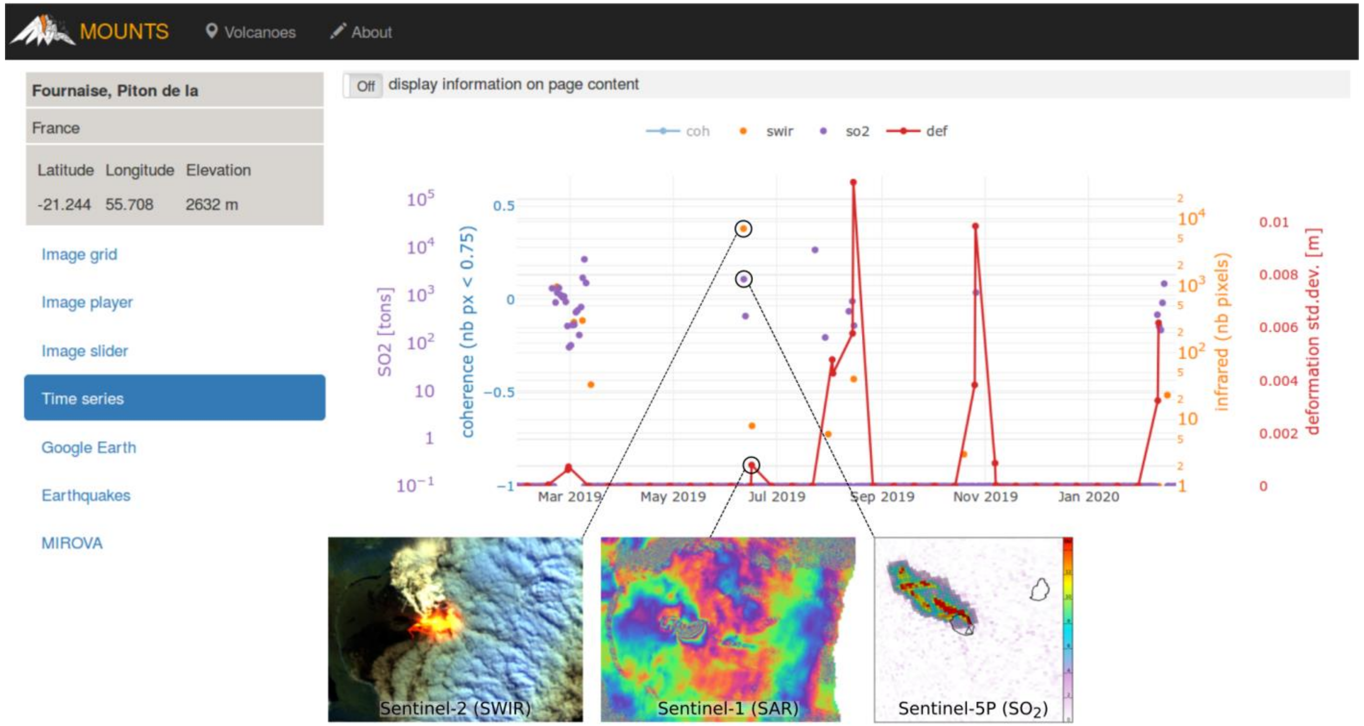
MONITORING APPLICATIONS and FUTURE PERSPECTIVES

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.



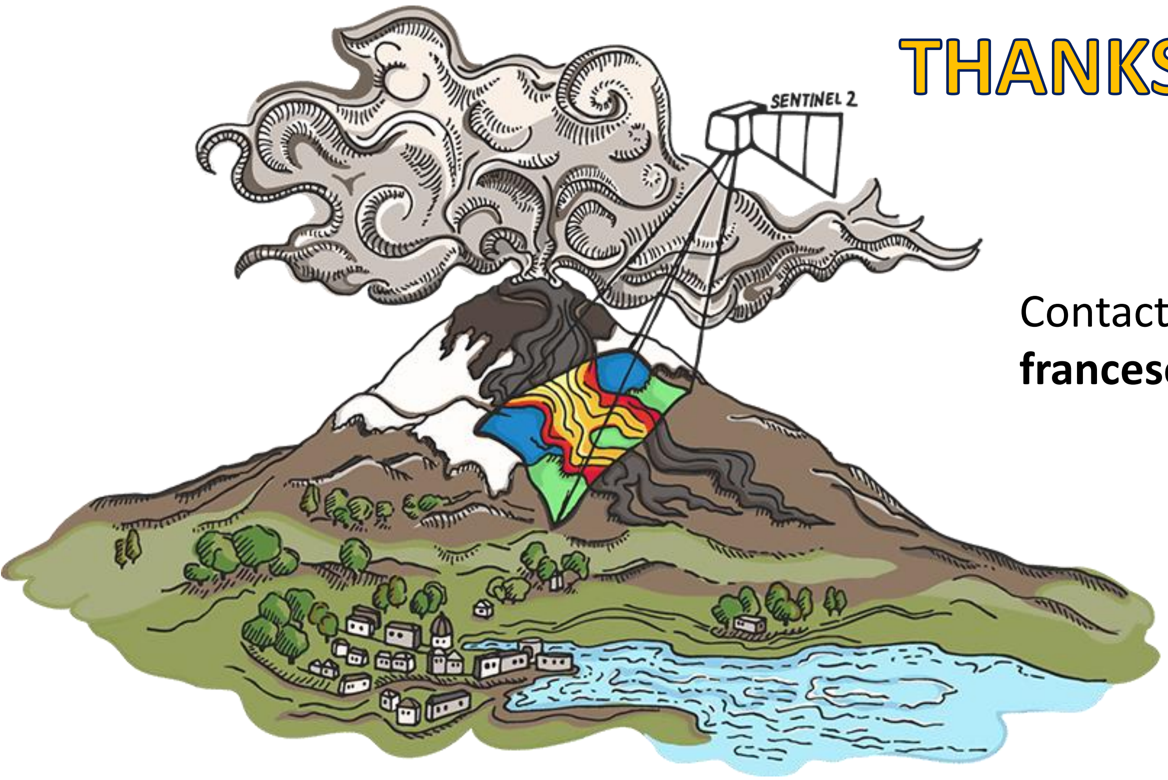


Modified from Valade et al., 2019

EGU General Assembly 2020

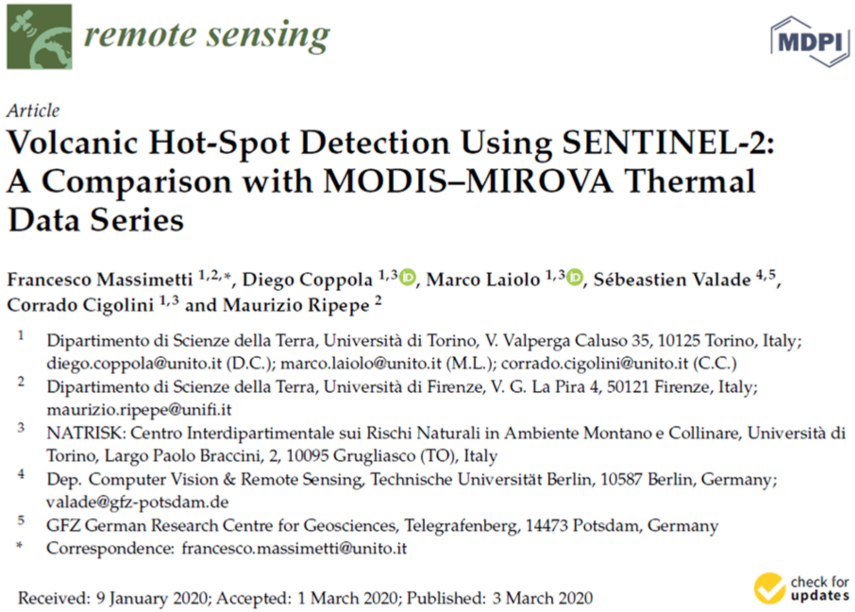
CONCLUSIONS

- 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!

Contacts:
francesco.massimetti@unito.it



remote sensing

MDPI

Article

Volcanic Hot-Spot Detection Using SENTINEL-2: A Comparison with MODIS–MIROVA Thermal Data Series

Francesco Massimetti [1,2,*], Diego Coppola [1,3], Marco Laiolo [1,3], Séveastien Valade [4,5], Corrado Cigolini [1,3] and Maurizio Ripepe [2]

1 Dipartimento di Scienze della Terra, Università di Torino, V. Valperga Caluso 35, 10125 Torino, Italy; diego.coppola@unito.it (D.C.); marco.laiolo@unito.it (M.L.); corrado.cigolini@unito.it (C.C.)
2 Dipartimento di Scienze della Terra, Università di Firenze, V. G. La Pira 4, 50121 Firenze, Italy; maurizio.ripepe@unifi.it
3 NATRISK: Centro Interdipartimentale sui Rischi Naturali in Ambiente Montano e Collinare, Università di Torino, Largo Paolo Braccini, 2, 10095 Grugliasco (TO), Italy
4 Dep. Computer Vision & Remote Sensing, Technische Universität Berlin, 10587 Berlin, Germany; valade@gfz-potsdam.de
5 GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
* Correspondence: francesco.massimetti@unito.it

Received: 9 January 2020; Accepted: 1 March 2020; Published: 3 March 2020

check for updates

Please cite: Massimetti et al., 2020 Volcanic Hot-Spot Detection Using SENTINEL-2: A Comparison with MODIS–MIROVA Thermal Data Series Remote Sens. 2020, 12(5), 820 https://www.mdpi.com/2072-4292/12/5/820

REFERENCES:

- Blackett, M. An overview of infrared remote sensing of volcanic activity. J. Imaging 2017, 3, 13.
- Coppola, D.; Laiolo, M.; Cigolini, C.; Delle Donne, D.; Ripepe, M. Enhanced volcanic hot-spot detection using MODIS IR data: Results from the MIROVA system. Geol. Soc. Lond. Spec. Publ. 2016, 426, 181–205.
- Harris, A.J.L. Thermal Remote Sensing of Active Volcanoes. A User's Manual; Cambridge University Press: Cambridge, UK, 2013; p. 736.
- Massimetti et al., 2020 Volcanic Hot-Spot Detection Using SENTINEL-2: A Comparison with MODIS–MIROVA Thermal Data Series Remote Sens. 2020, 12(5), 820
- Murphy, S.W.; de Souza Filho, C.R.; Wright, R.; Sabatino, G.; Pabon, R.C. HOTMAP: Global hot target detection at moderate spatial resolution. Remote Sens. Environ. 2016, 177, 78–88.
- Valade, S.; Ley, A.; Massimetti, F.; D'Hondt, O.; Laiolo, M.; Coppola, D.; Loibl, D.; Hellwich, O.; Walter, T.R. Towards Global Volcano Monitoring Using Multisensor Sentinel Missions and Artificial Intelligence: The MOUNTS Monitoring System. Remote Sens. 2019, 11, 1528.