Investigating active volcanism from infrared satellite imagery: the role of multi-temporal, multi-spectral and multi-mission approaches in the Open Data era.

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OBSERVING THERMAL VOLCANIC ACTIVITY BY SATELLITE

Thermal volcanic activity may be observed, monitored and investigated by satellite with particular reference to:

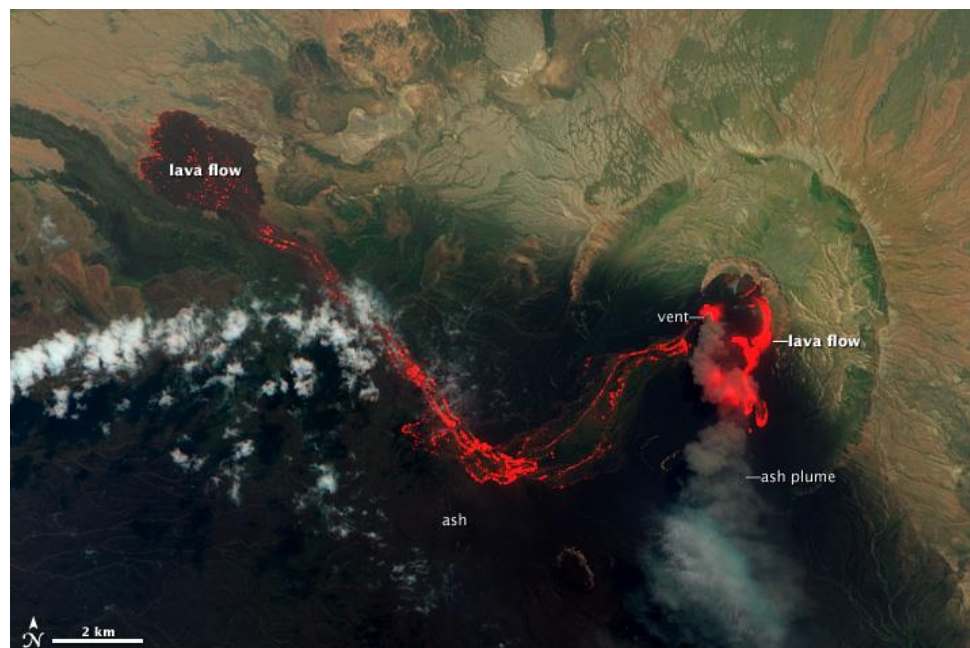
1. Surface thermal anomalies (lava bodies, fumarole fields, gas emissions, pyroclastic flows, etc.) detection.

2. Early Warning purposes.

3. Identification of possible pre-eruptive hotspots.

4. Thermal feature investigation and quantitative characterization.

5. Thermal Activity evolution and trend.



OBSERVING THERMAL VOLCANIC ACTIVITY BY SATELLITE

A satellite-based volcanic hotspot detection system may provide (at least) the following information (Coppola et al. 2020):

1. <u>Presence of thermal anomalies</u> → reveals new (e.g. thermal unrest) or previous activity still in progress

2. <u>Intensity</u> → Thermal flux can be derived by satellite, being a measure of radiated thermal energy; it can be used to calculate the ***area*** and/or the ***temperature*** of the lava body, estimating the size of the phenomenon underway. Moreover, during effusive eruptions, the thermal flux can be used to calculate the ***effusion Rate*** or ***Time Averaged lava Discharge Rate*** (TADR), which is a critical parameter to assess eruption intensity and perform the lava flow simulation

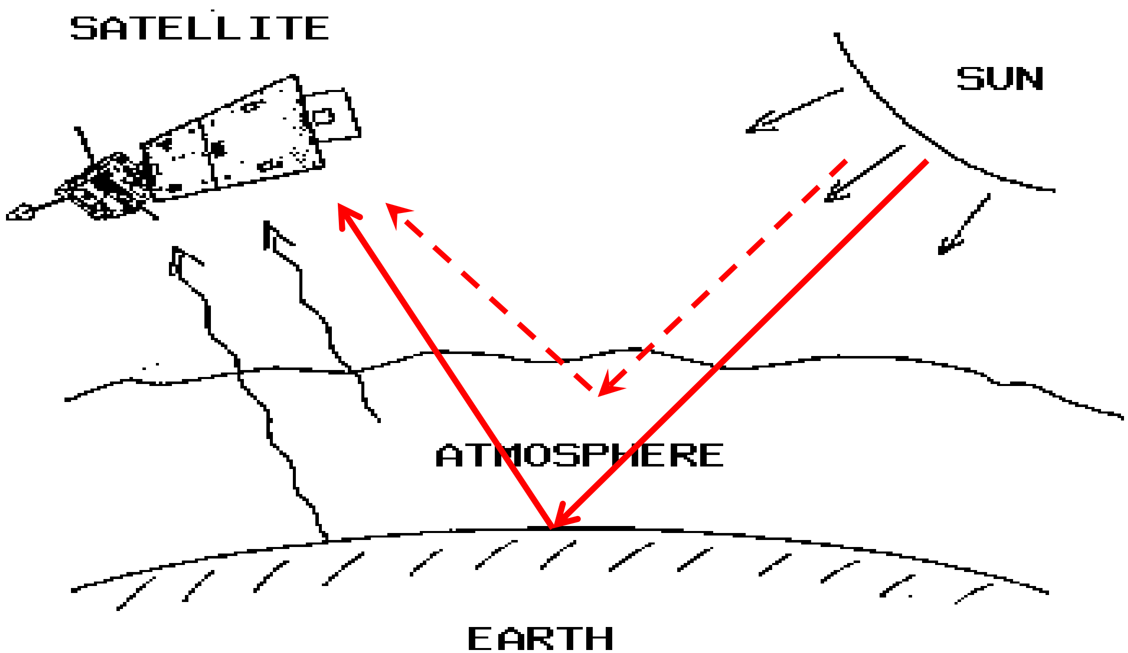
OBSERVING THERMAL VOLCANIC ACTIVITY BY SATELLITE

3. Location/dimension of hotspots → Locating the thermal anomaly with precision is fundamental to recognize the type of activity in progress, to assess the ***areas at risk***, to map thermal features and to run forecast models (e.g. forecasting lava flows paths; Harris et al., 2016)

4. Thermal Activity evolution and trend → Satellite observations are ***repetitive*** and can be provided at variable frequency (with refreshing times ranging from days to minutes), thus they are able to track ***relative changes*** in thermal output as a time series.

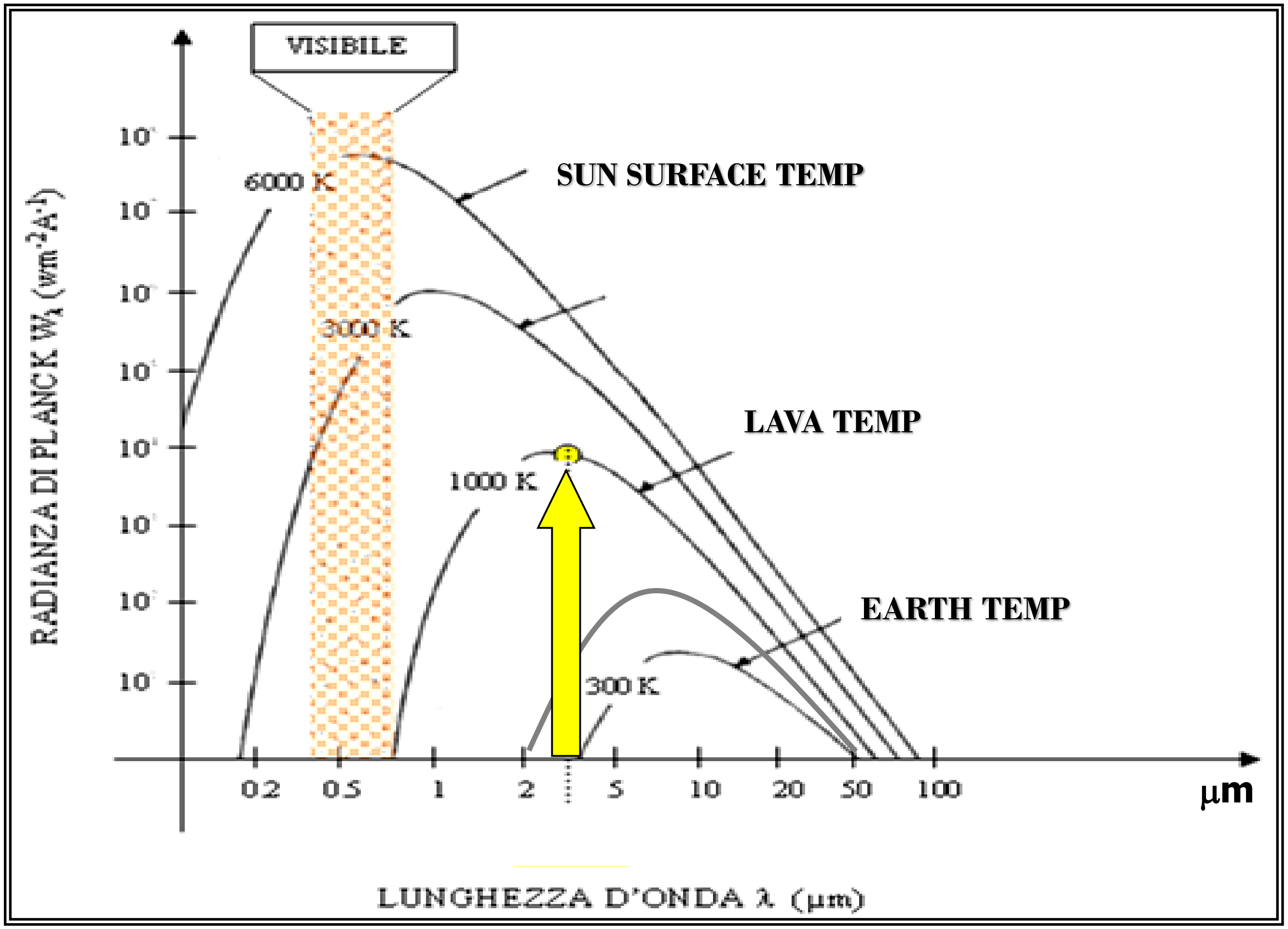
SATELLITE EARTH OBSERVATION PRINCIPLES

What do we measure from space (passive systems)?



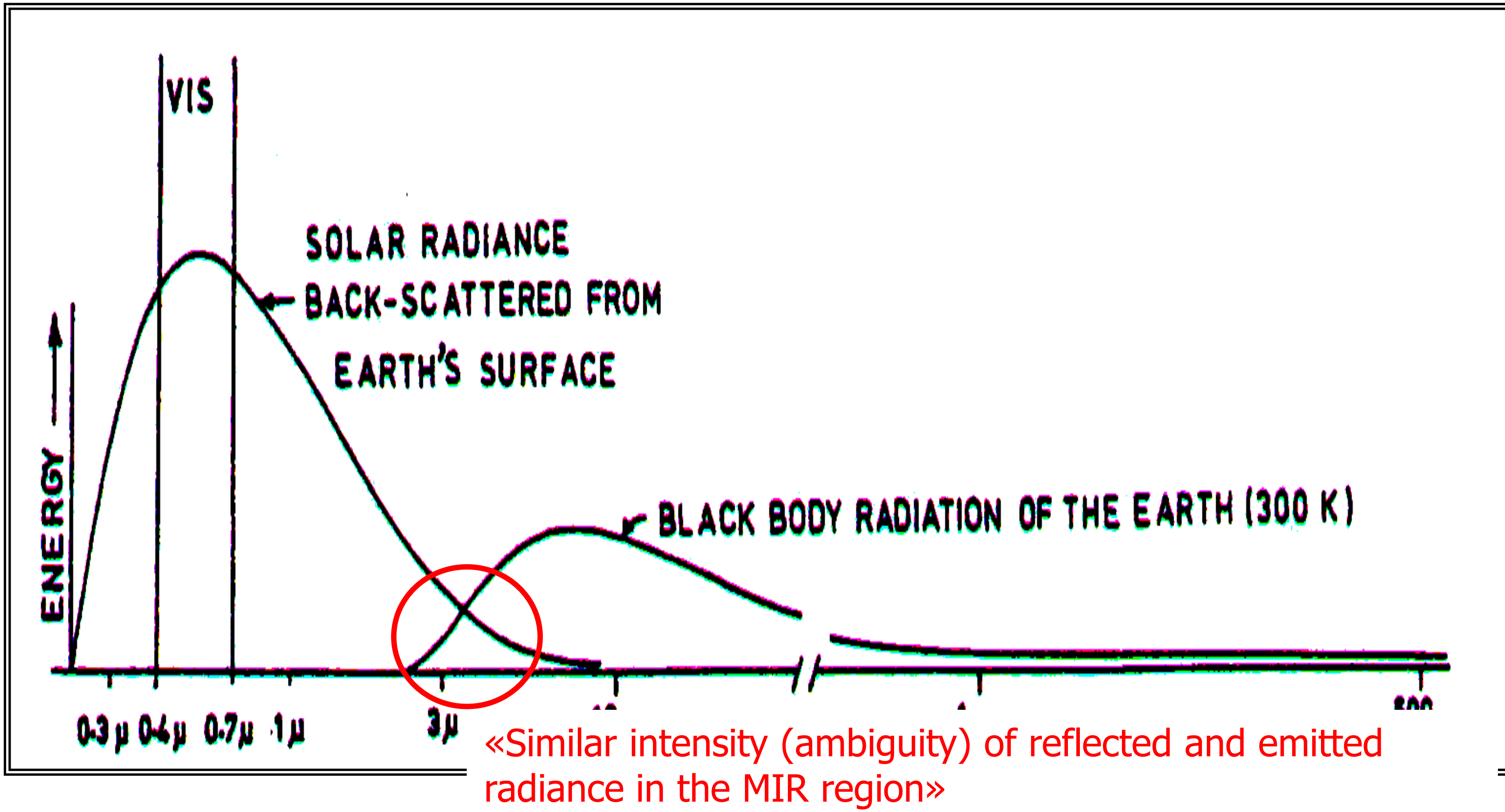
Passive Satellite systems generally measure Earth emitted and Solar Reflected Radiances (Atmosphere may contribute to both)

VOLCANIC HOTSPOTS DETECTION FROM SPACE: PHYSICAL BASIS



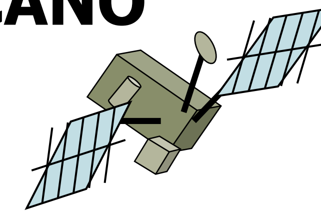
Lava bodies (~ 600 to 1300 K) emit the maximum of their thermal radiation in the **mid-infrared band (MIR) at wavelengths around 3-5 µm**. Magmatic sources also show a large emission at shorter wavelengths (~2.0-2.5 µm, SWIR).

EARTH'S SURFACE REFLECTED AND EMITTED RADIANCE

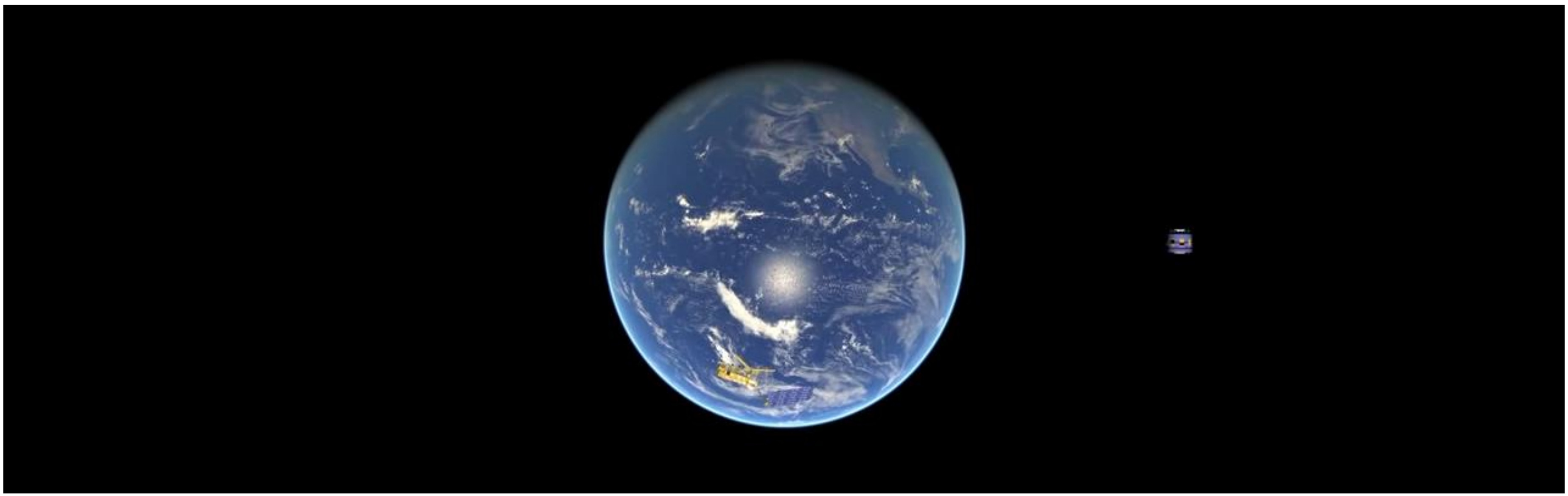


In the MIR spectral band, in daytime, the contribution of reflected solar radiation to the thermal radiation emitted by a hot surface can be still significant and must be taken into account

MAIN SATELLITE PLATFORMS FOR VOLCANO MONITORING AND INVESTIGATION



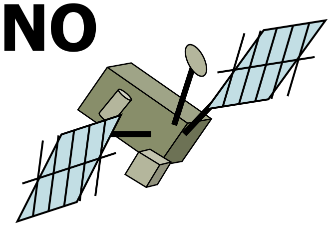
Near-polar (Low Earth Orbit - LEO) and Geostationary (GEO) orbiting systems



LEO → Higher spatial resolution (e.g. up to tens of meters)

GEO → Better temporal resolution (e.g. up to a few minutes)

MAIN SATELLITE PLATFORMS FOR VOLCANO MONITORING AND INVESTIGATION

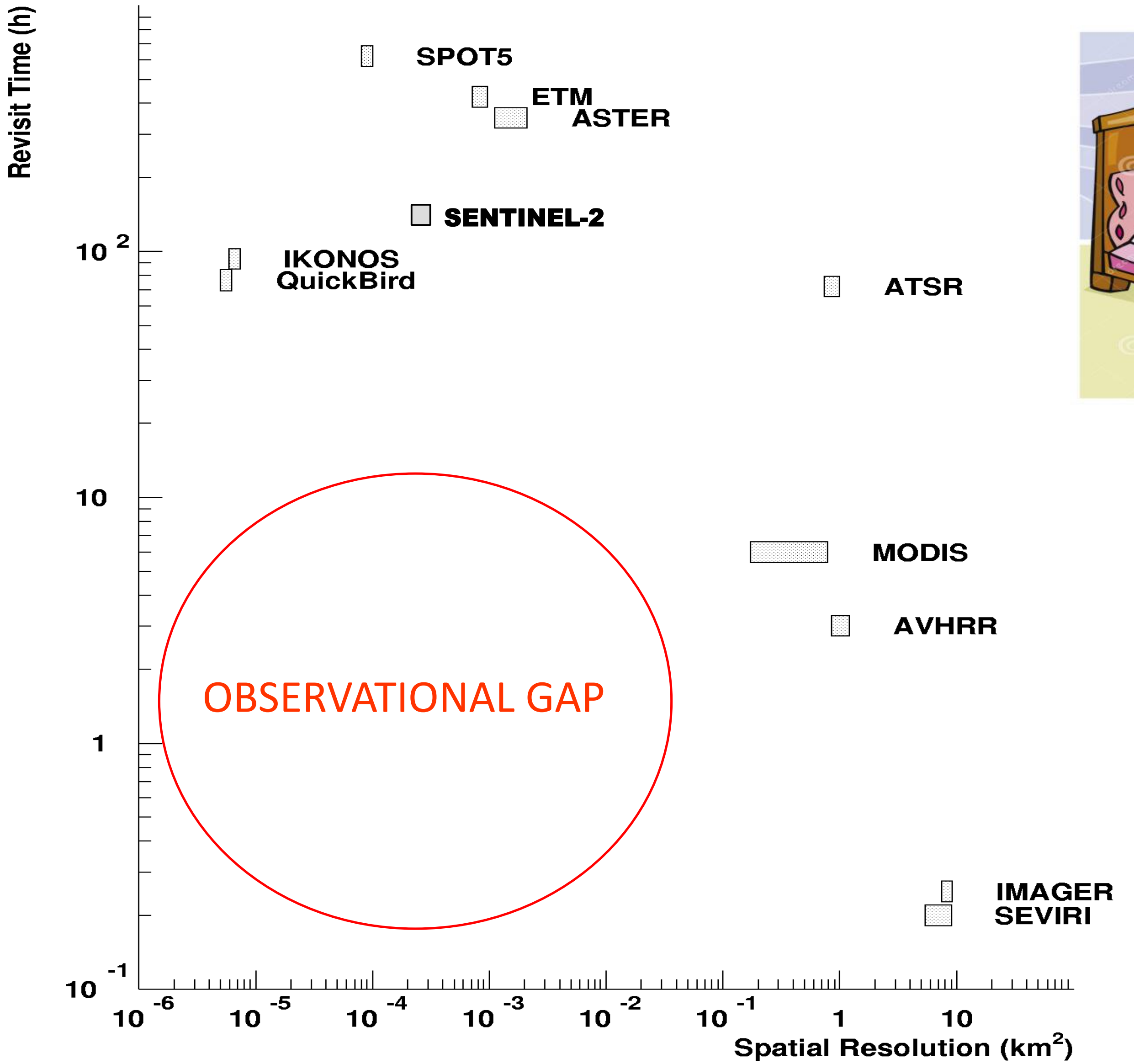


Incresing spatial resolution

Satellite/Sensor	Spatial Resolution	Revisit time	Orbit Type
SENTINEL-2/MSI	10 – 30 m	*~5 days*	*LEO*
EOS/ASTER	*15 - 90 m*	*16 days*	*LEO*
LANDSAT/TM-OLI	*30 - 120 m*	*14 days*	*LEO*
NPP-Suomi/VIIRS	375 – 750 m	*~12 hours*	*LEO*
EOS/MODIS	*1 Km*	*~10 hours*	*LEO*
NOAA/AVHRR	*1.1 km*	*6 hours*	*LEO*
GOES-R/ABI	*2 Km*	*10 minutes*	*GEO*
HIMAWARI-8/AHI	2 km	*10 minutes*	*GEO*
MSG/SEVIRI	*3 Km*	*15 minutes*	*GEO*

Incresing temporal resolution

Constraints of EO passive systems



Hotspot detection Methods

RST$_{VOLC}$ (Robust Satellite Techniques)

$$\otimes_{MIR}(x,y,t) = \frac{T_{MIR}(x,y,t) - \mu_{MIR}(x,y)}{\sigma_{MIR}(x,y)} \qquad \otimes_{\Delta MIR-TIR}(x,y,t) = \frac{\Delta T_{MIR-TIR}(x,y,t) - \mu_{\Delta MIR-TIR}(x,y)}{\sigma_{\Delta MIR-TIR}(x,y)}$$

Multi-temporal & Multi-spectral approach (MIR & TIR)

Tramutoli, 1998; Pergola et al., 2004; Marchese et al. 2011

NHI (Normalized Hotspot Indices)

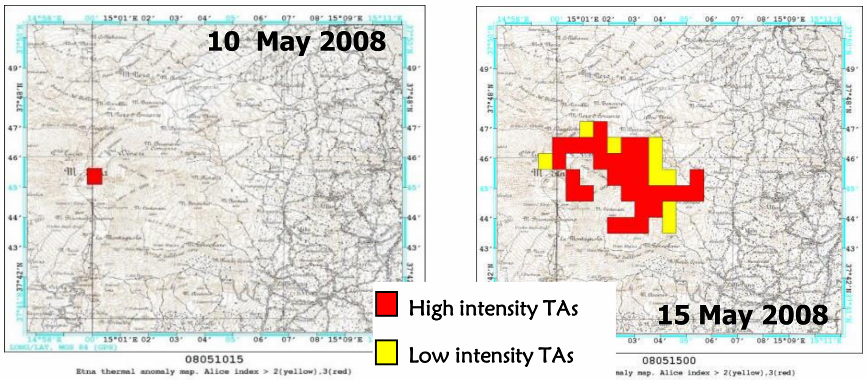
$$NHI_{SWIR} = \frac{L_{2.2} - L_{1.6}}{L_{2.2} + L_{1.6}} \qquad NHI_{SWNIR} = \frac{L_{1.6} - L_{0.8}}{L_{1.6} + L_{0.8}}$$

Multispectral approach (SWIR & NIR)

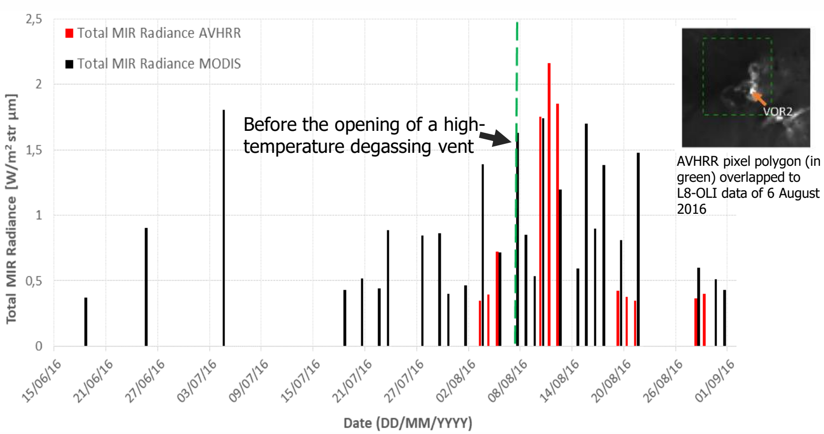
Marchese et al., 2019

RST_{VOLC} (Robust Satellite Techniques)

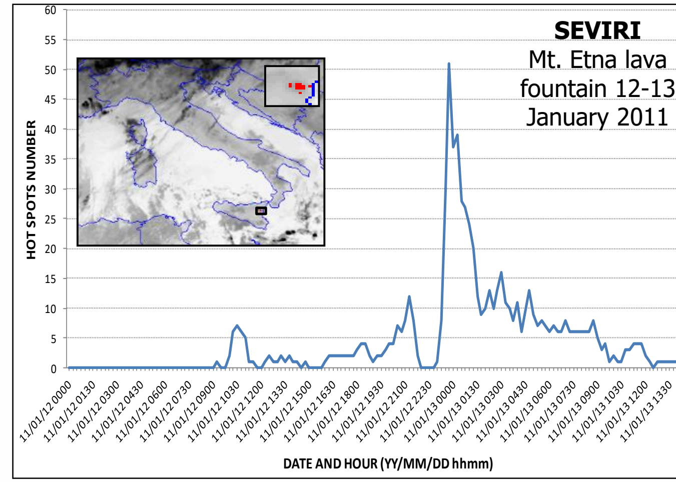
Space-time evolution monitoring of volcanic Thermal anomalies (TA) (Mt. Etna, May 2008)

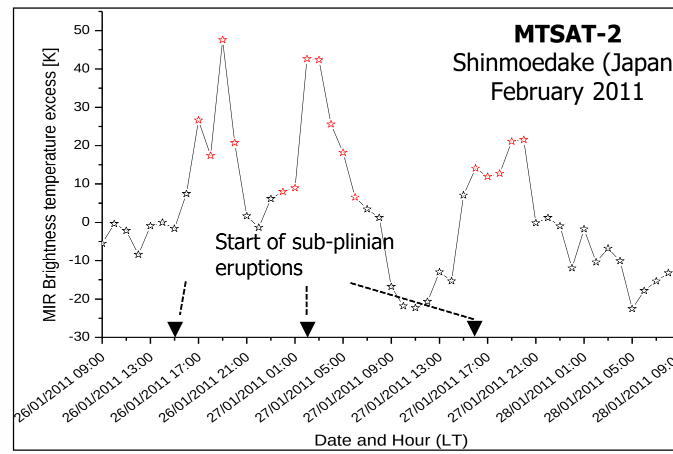


Identification of thermal unrest phases (Etna, July 2016)



Continuous monitoring of short-lived events





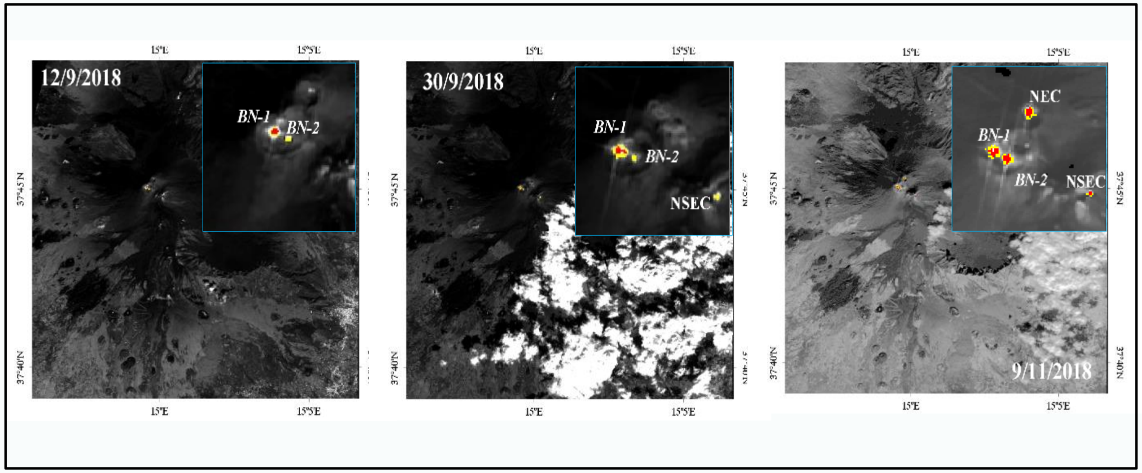
More suited for medium-coarse (≥ 1 km) spatial resolution data at short (< 12 h) and very short (minutes) revisit time, for which a highly populated multi-annual dataset of satellite observations is available.

Applied to: AVHRR, MODIS, SEVIRI, MTSAT, VIIRS, ASTER

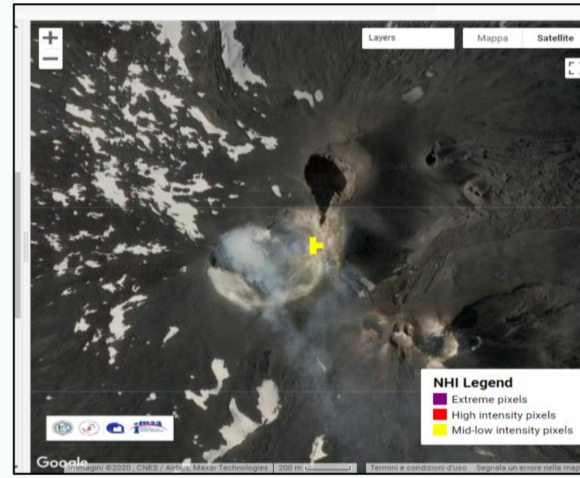
NHI (Normalized Hotspot Indices)

Accurate localization of active vents

Etna (Italy) - September-November 2018

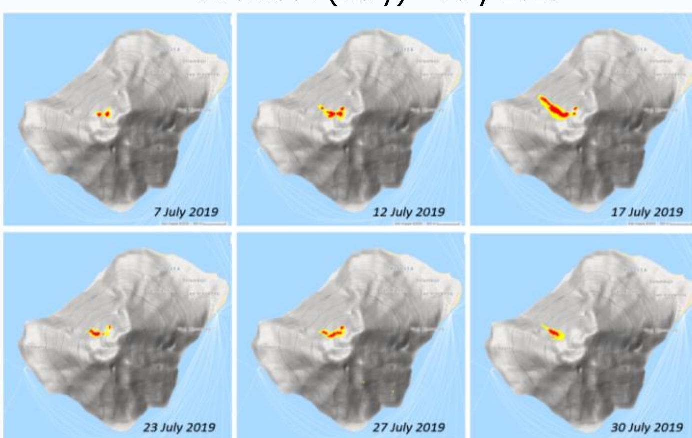


Etna (Italy)- July 2016



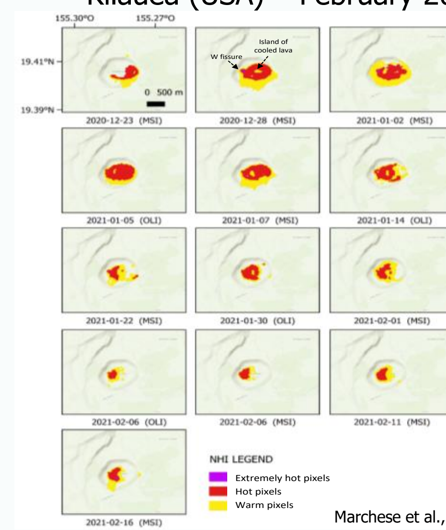
Detailed mapping of lava flows/lakes

Stromboli (Italy) – July 2019



Genzano et al., 2020

Kilauea (USA) – February 2021



Marchese et al., 2021b

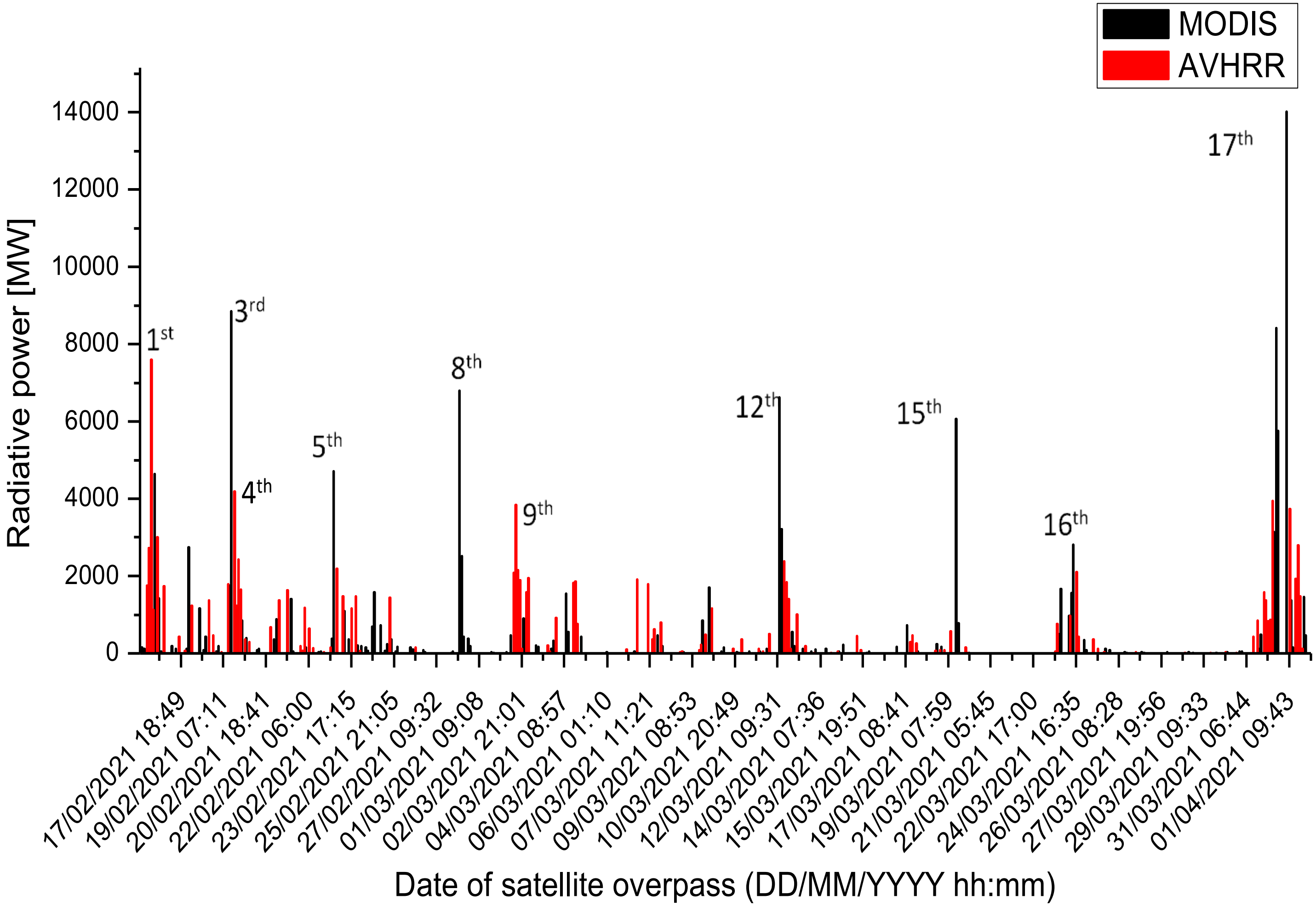
More suited for mid-high (i.e. < 50 m) spatial resolution data at medium (i.e. 1-2 weeks) revisit time

Running operationally on MSI and OLI; Applied to: TM, ETM+ and ASTER

Results of data integration

(Mt. Etna paroxsysms of Feb-Apr 2021)

Volcanic Radiative **Power** (AVHRR+MODIS radiances)

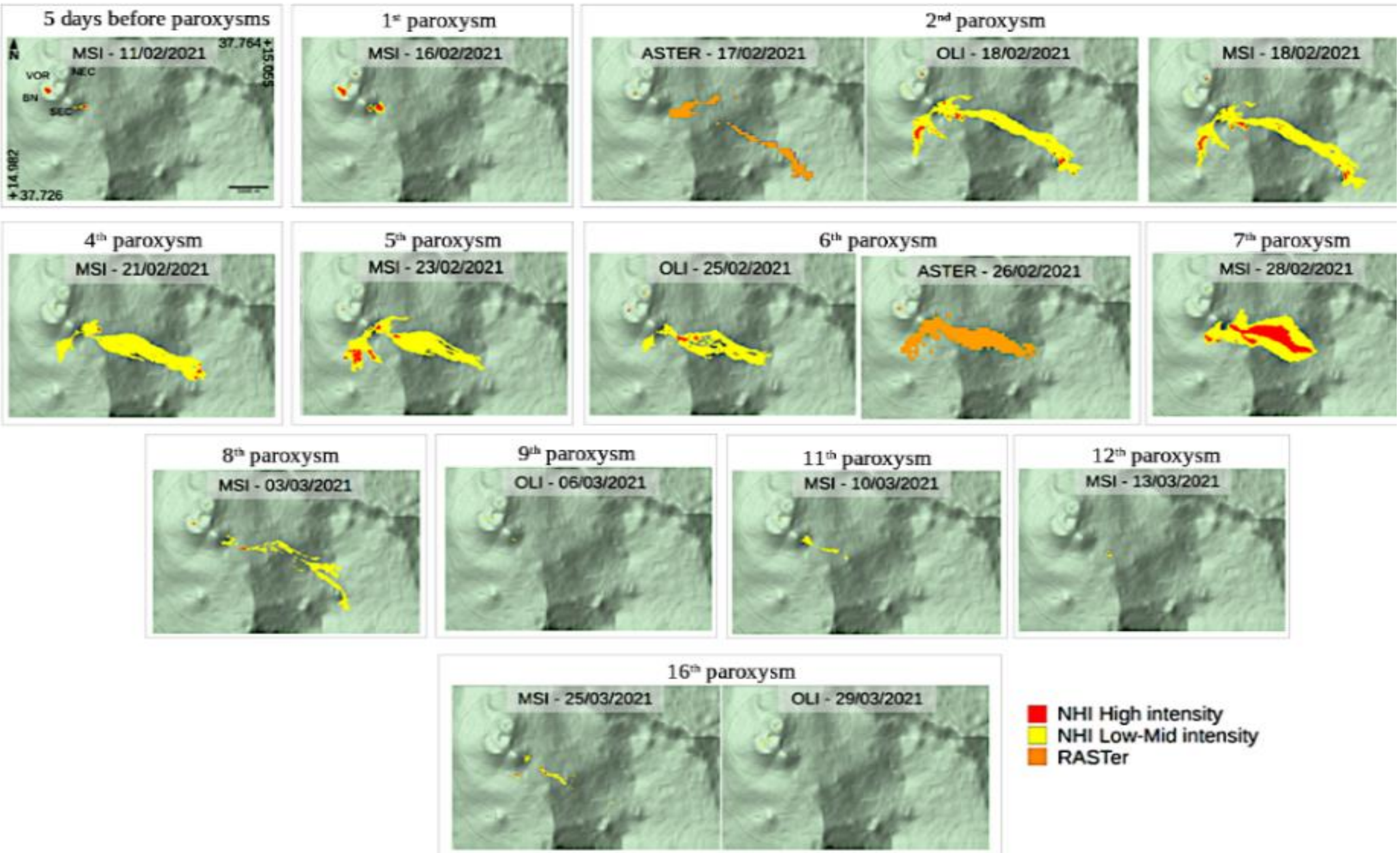


Marchese et al., 2021a

Results of data integration

(Mt. Etna paroxsysms of Feb-Apr 2021)

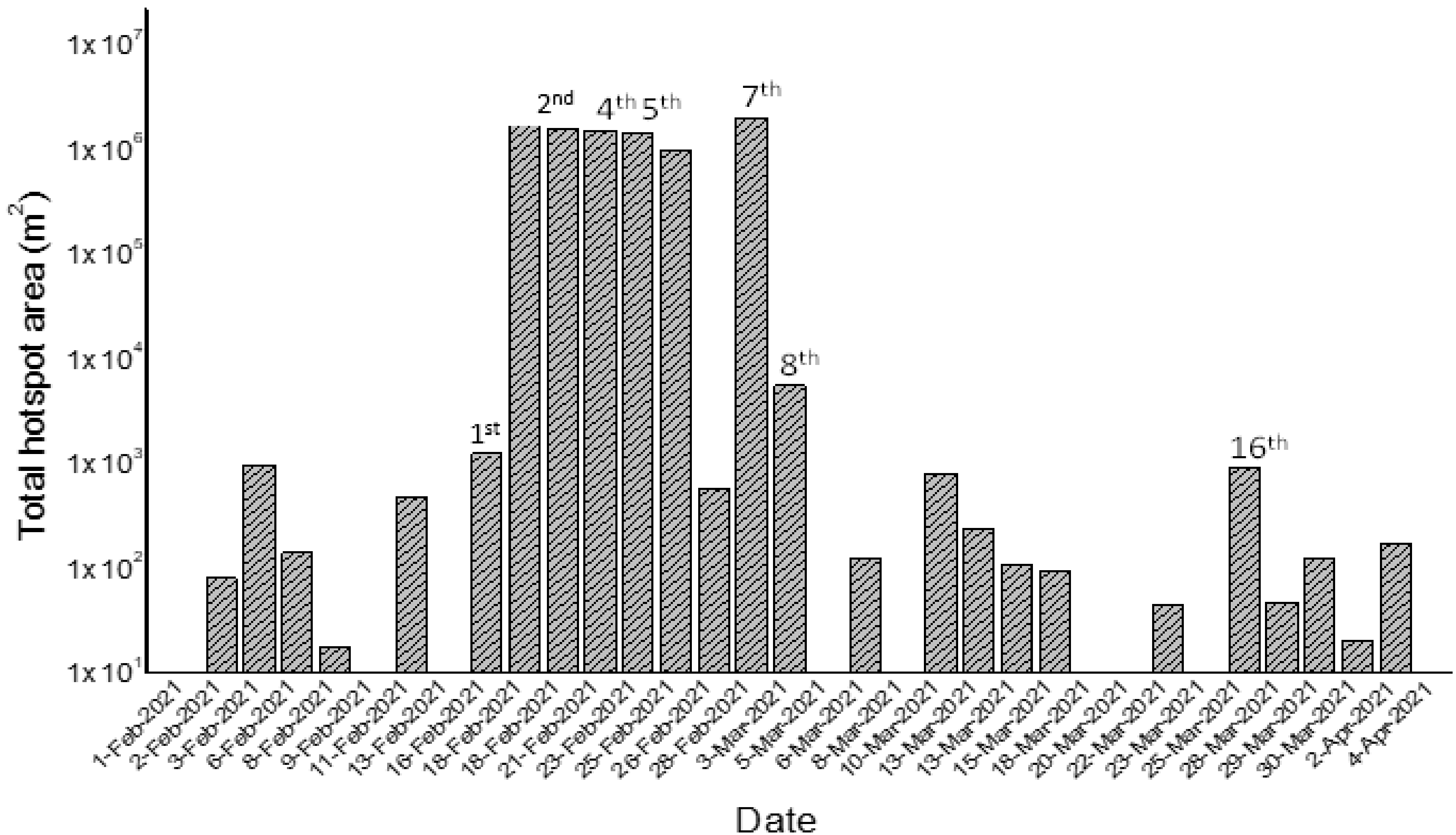
Size, extent and location of **Lava flow** (OLI+MSI+ASTER maps)



Results of data integration

(Mt. Etna paroxsysms of Feb-Apr 2021)

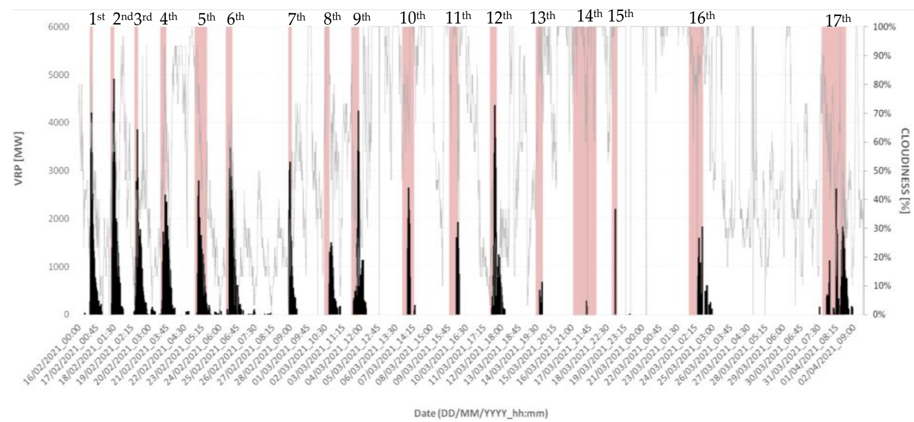
Total **hotspot area** (OLI+MSI+ASTER)

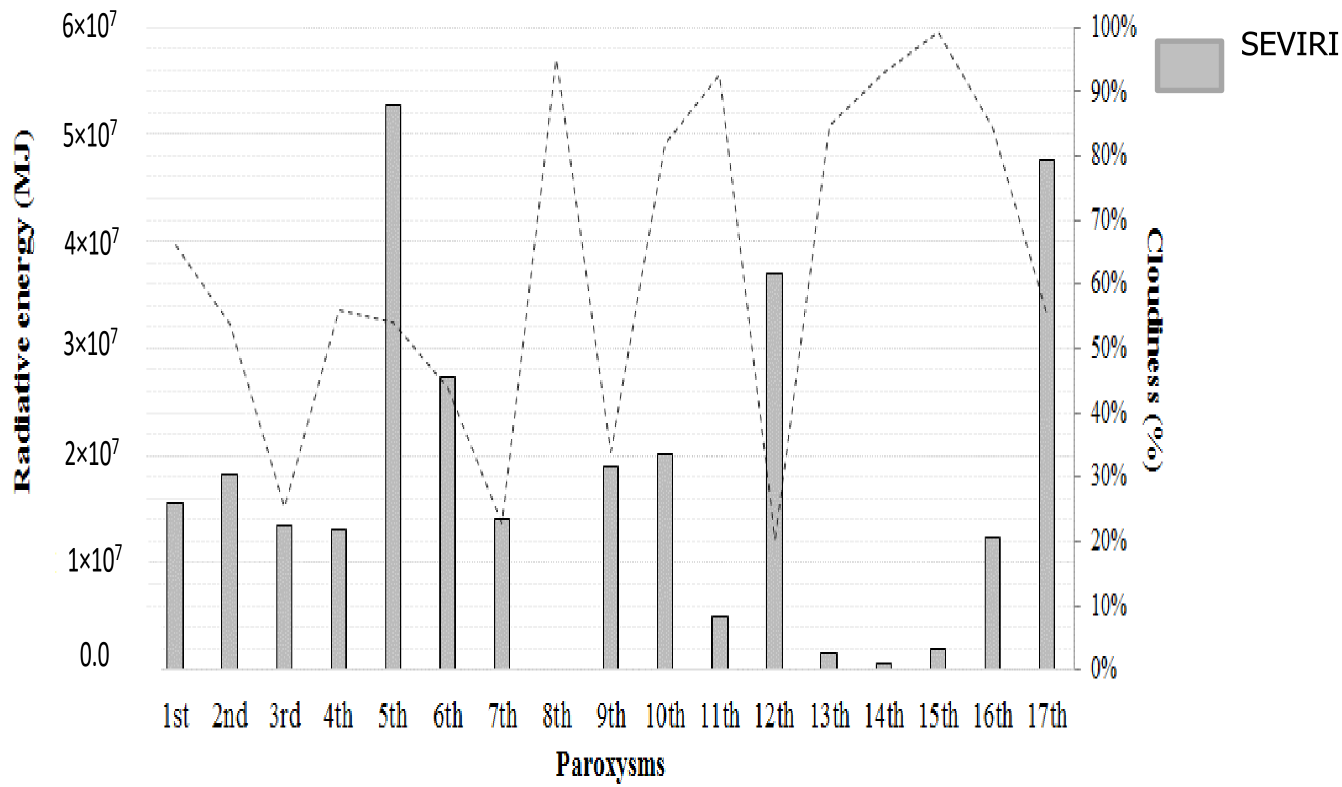


Results of data integration

(Mt. Etna paroxsysms of Feb-Apr 2021)

Paroxysm Radiative **Energy**
(SEVIRI IR time series data)



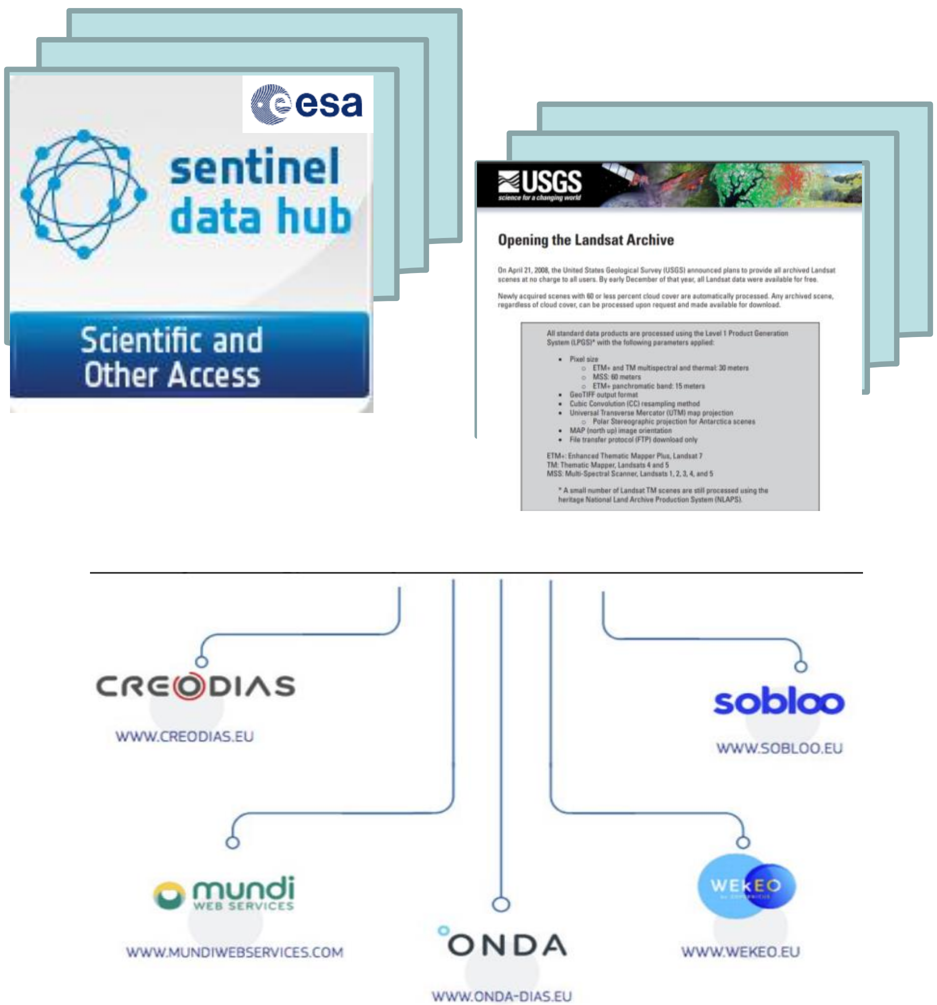


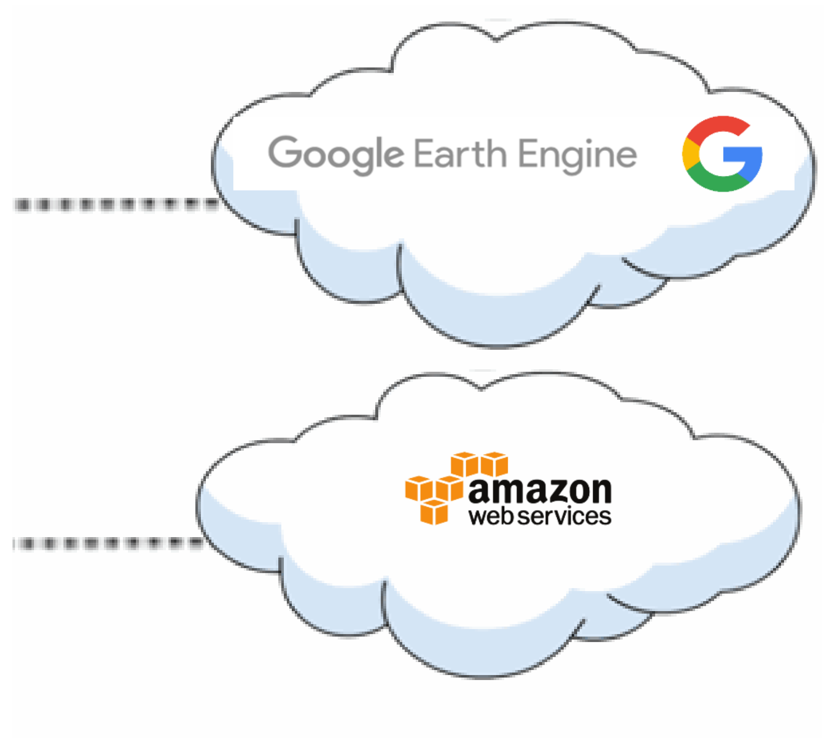
Open data & Open Tool

Massive amounts of data
Full, open and free-of-charge

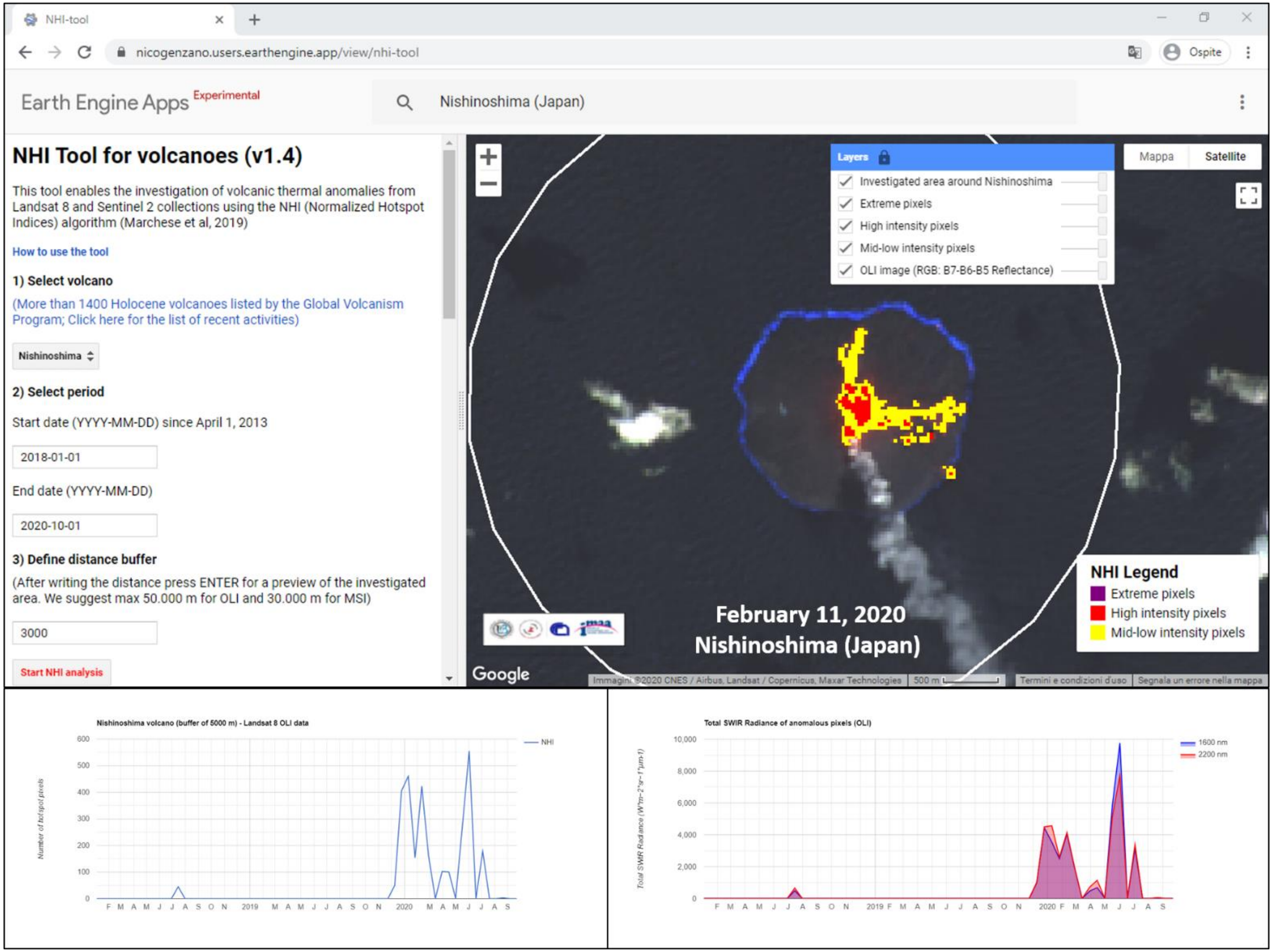
+

Open and free cloud computing tools and facility



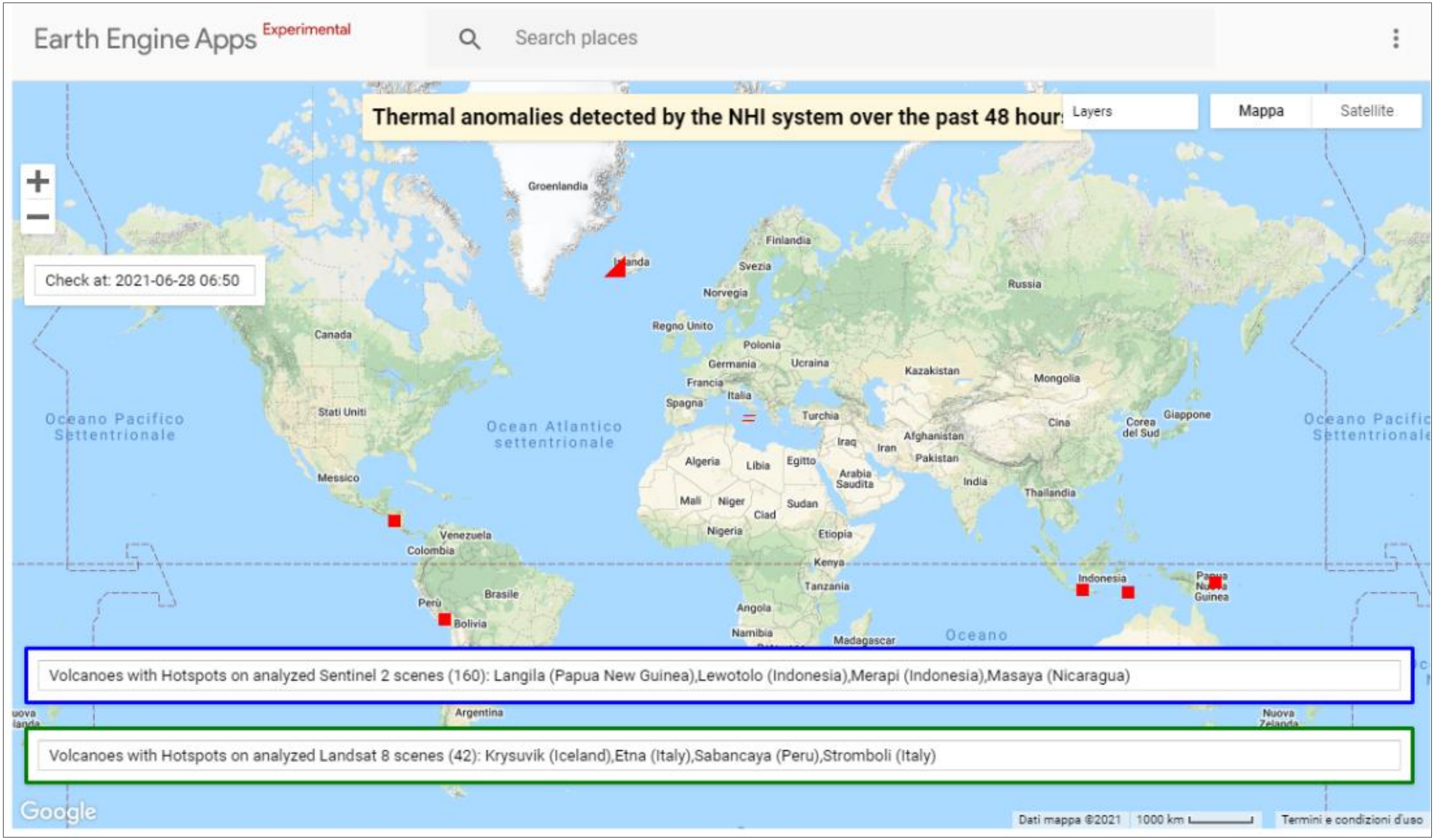


A Google Earth Engine tool for active volcanoes investigation



NHI tool available at: *https://nicogenzano.users.earthengine.app/view/nhi-tool*

Automated worldwide volcano monitoring through S2-MSI and L8-OLI data



https://sites.google.com/view/nhi-tool/home-page

Conclusion

- Thermal anomalies flagged by RST_{VOLC} using low spatial/high temporal resolution satellite data, including subtle hotspots, may be further investigated with a high level of detail using ASTER, OLI and MSI (through NHI)

- Integration of different satellite data/products may help in better characterizing thermal anomalies and inferring eruption dynamics, as for Mt. Etna paroxysmal events of 2021

- The NHI tool/system may provide relevant information especially in remote areas, where traditional surveillance systems often lack

- Open data and tools (e.g. GEE) may open new insights in active volcanism monitoring and investigations at unprecedented space and time scales

References

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