Volcanic cloud satellite retrieval: an infrared and millimeter-wave multisensor approach using statistical and machine learning methods

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Abstract

This presentation participates in OSPP

EGU

Outstanding Student & PhD candidate Presentation contest

Outline

- Aim
- Satellite data
- Methods
- Results
- Conclusions & Beyond

Aim

Develop a methodology capable of monitoring volcanic ash clouds during first hours.

- Proximal Clouds: near source ash clouds, microwave millimetre-wave (MW-MMW)
- Distal Clouds: volcano's vent distant ash clouds, thermal-infrared (TIR)

The algorithm (MW-MMW and TIR-IR):

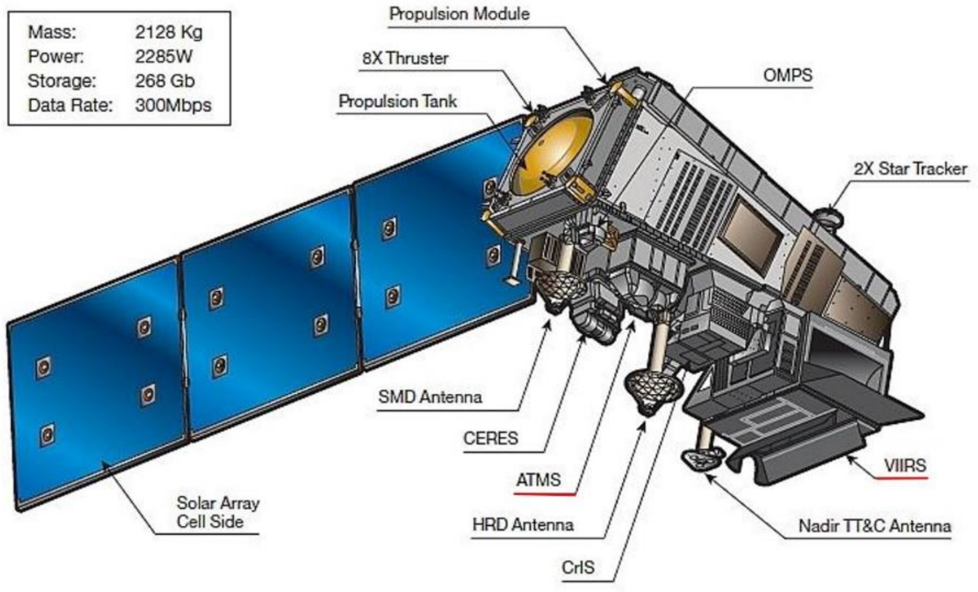
- Cloud Identification
- Mass Estimate

Case studies:

- Kelud 2014
- Calbuco 2015
- Etna 2021

Satellite data

Satellite	Suomi-NPP				
Sensors	VIIRS (TIR-IR)		ATMS (MMW—MW)		
Spatial Resolution	750 m	375 m	75 km	32 km	16 km
Unit	λ (μm)	λ (μm)	ν (GHz)	ν (GHz)	ν (GHz)
Bands (22 each)	0.412 0.445 0.488 0.555 0.672 0.746 0.865 1.240 1.378 1.610 2.250 3.700 4.050 8.550 10.763 12.013	0.700 0.640 0.865 1.610 3.740 11.450	23.8 31.40	50.30 51.76 52.80 53.596±0.115 54.90 54.94 55.50 57.29 57.29±0.217 57.29±0.322±0.048 57.29±0.322±0.022 57.29±0.322±0.010 57.29±0.322±0.004 88.20	165.50 183.31±7.0 183.31±4.5 183.31±3.0 183.31±1.8 183.31±1.0



Credit: European Space Agency

Suomi-NPP

The satellites objective is to provide atmospheric measurements such as:

- temperature
- humidity
- clouds
- wind speed on sea surface
- atmospheric ozone content

Suomi-NPP is a sun-synchronous, near-circular, polar orbit satellite positioned at an altitude of 824km, with an inclination angle of 98.74° , a period of 101 minutes, a repeat cycle of 16 days. It is in orbit since 28 October 2011.

Methods: Two detection approaches

1

Microwave-Spectral-Difference (MSD)

1.1

Near the volcanic vent, most of the volcanic ash clouds are opaque in the infrared region being optically thick.

The MSD is a two step identification procedure [Marzano et al. 2013]:

1. **(Window)** All the clouds are detected in the scene:
   - $MSD_W = BT_{165\ GHz} - BT_{88.20\ GHz}$
2. **(Absorption)** Ash clouds are separated from meteorological clouds:
   - $MSD_A = BT_{183\ GHz} - BT_{165\ GHz}$

Brightness Temperature Difference (BTD)

1.2

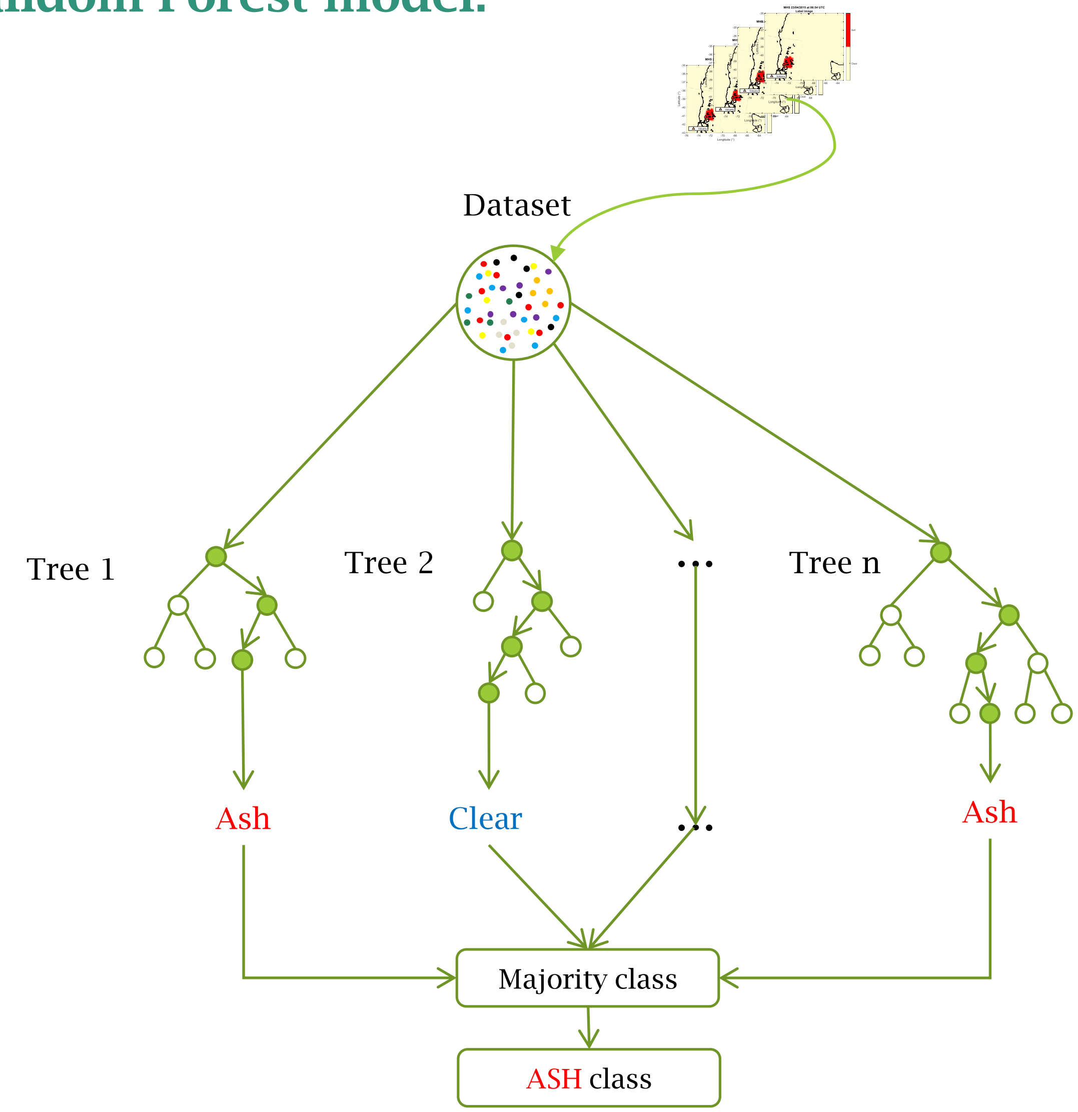
In the range of 8 to 14 μm silicate particles absorb more radiation at around 8-11 μm, whereas water particles absorb more at higher wavelengths (12-14 μm) [Prata et al. 2001].

Ash clouds can be identified by selecting pixels which have a BTD below a fixed threshold ($\boldsymbol{t_{BTD}}$) [Wen & Rose 1994]:

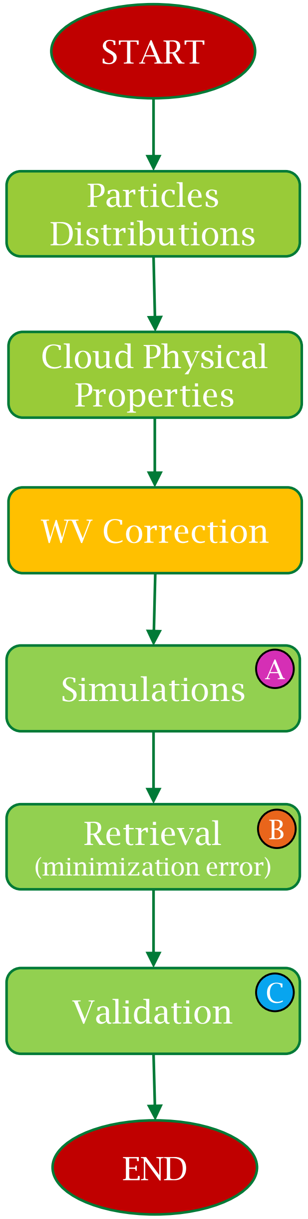
$$BT_{11\mu m} - BT_{12\mu m} < t_{BTD}$$

2

Random Forest model:



Methods: Mass estimate



A Radiative transfer differential equation solved considering one-layer and two-layers approximation [Solimini 2016]:

$$BT_H = BT_0 e^{\tau(0,H)} + \int_0^H \alpha_v (1-\omega)\epsilon T e^{-\tau(s,H)} ds \quad (K)$$

A Mass estimate [Solimini 2016]:

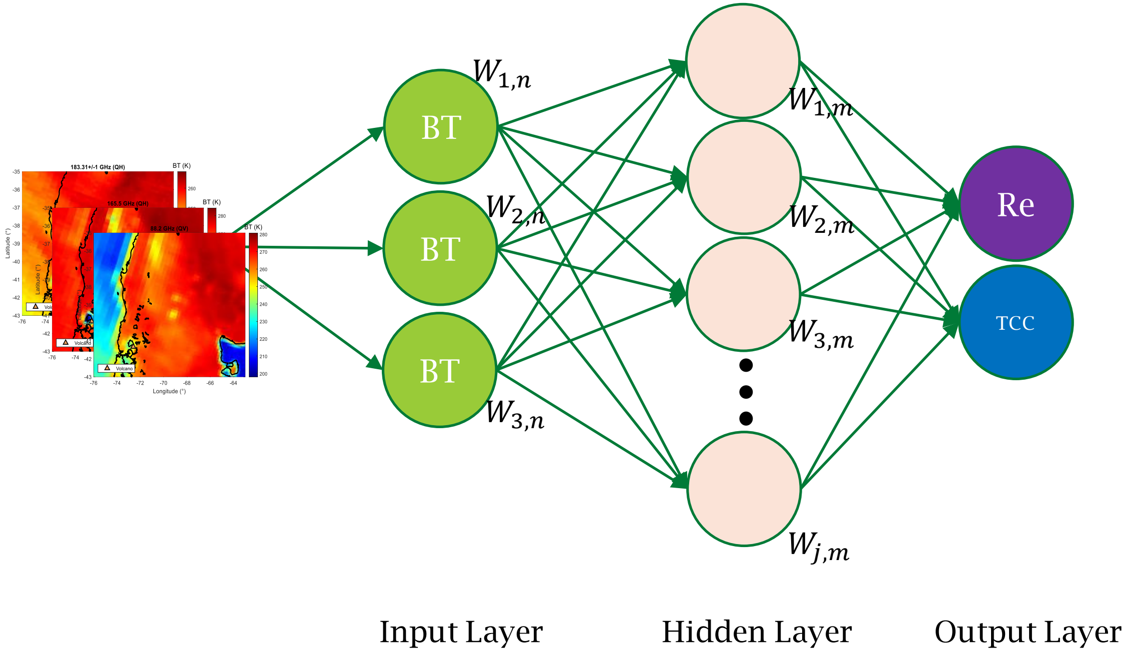
$$TCC = \frac{4}{3}\pi H \int_{r_{min}}^{r_{max}} \rho(r) r^3 N(r) dr \quad (kg/m^2)$$

C Parametric formula [Marzano et al. 2018]:

$$TCC_{EPR} = a_t \left(\frac{\rho}{\rho_0}\right) + b_t \left(\frac{\rho}{\rho_0}\right) BT_f \quad (kg/m^2)$$

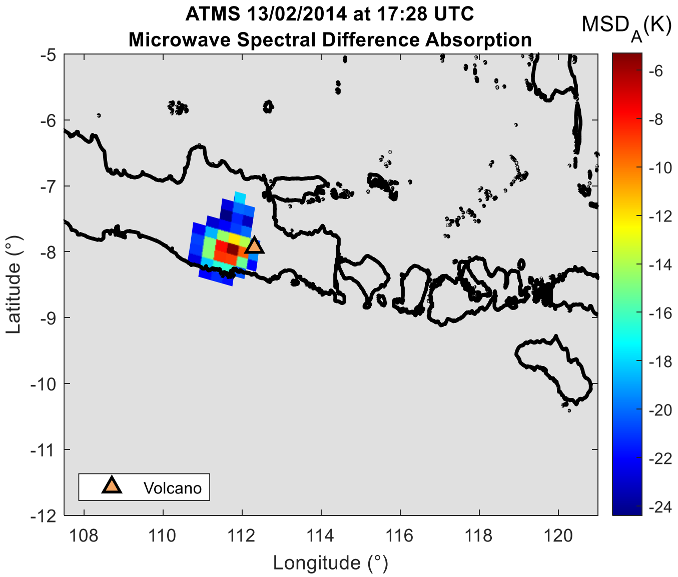
$$a_t = 63.84;\ b_t = -0.2564;\ \rho = \rho_0 = 2500\ (kg/m^2)$$

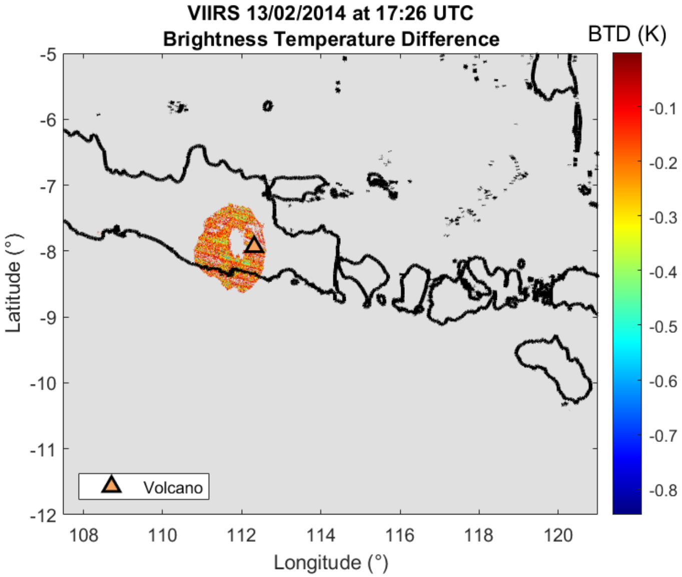
B **Neural Network architecture** used to solve a multiple regression problem for both TIR-IR and MW-MMW signals.

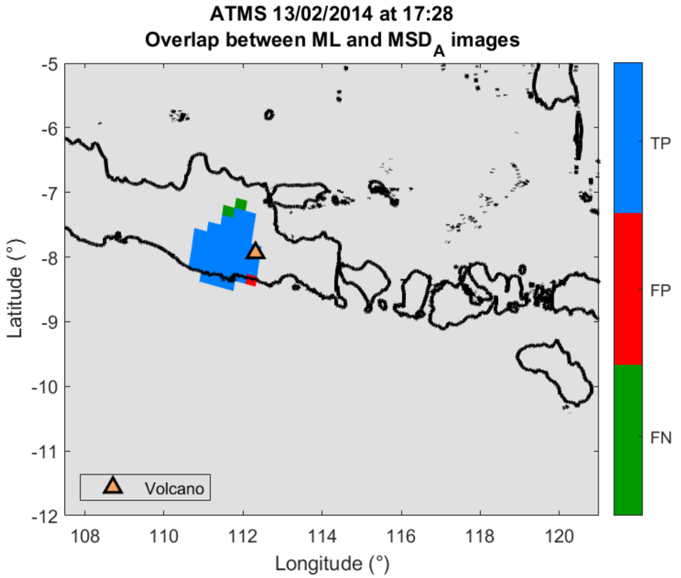


Results: Kelud

Near source cloud detected by MW-MMW and TIR-IR sensors, with instantaneous total mass estimations for Kelud eruption occurred in 2014.



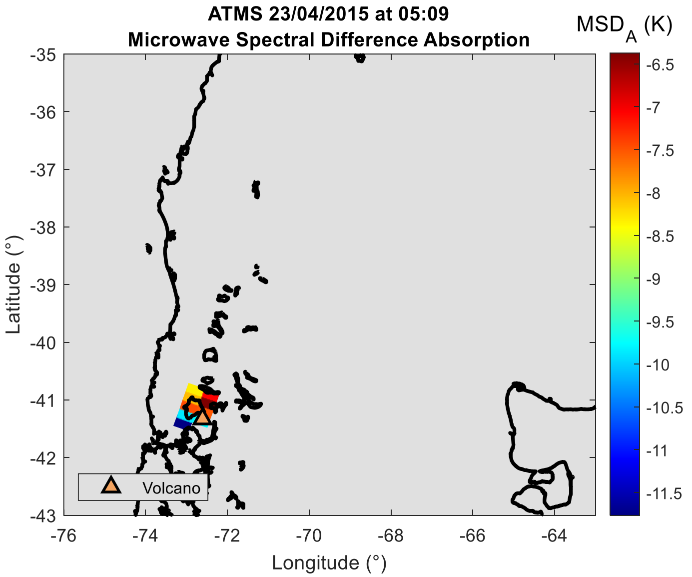


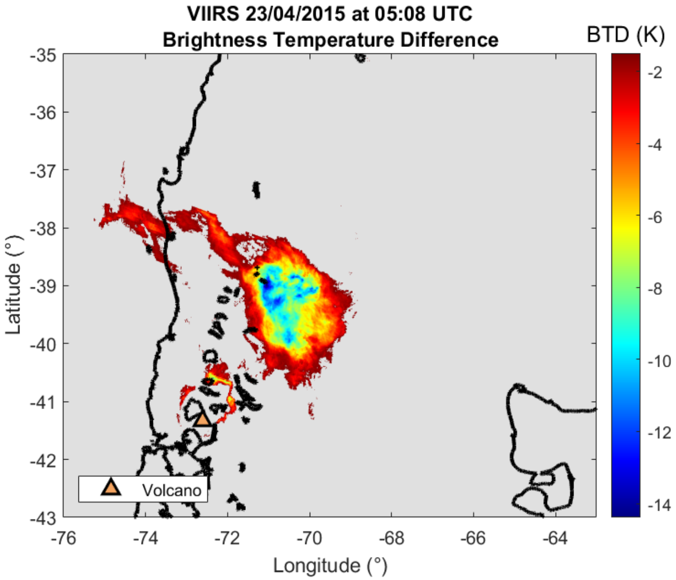


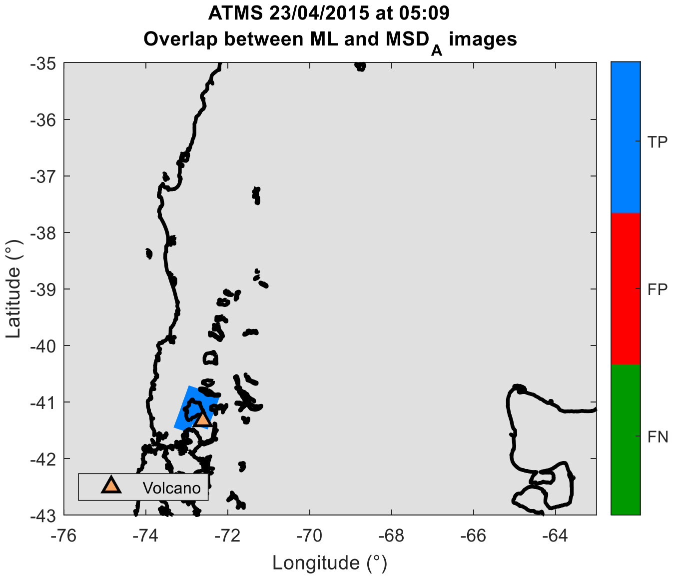
Sensor	EPR	MLE	NN
ATMS	$1.53e^{11}$ kg	$1.30e^{10}$ kg	$1.50e^{10}$ kg
VIIRS	✗	$2.67e^{9}$ kg	$1.19e^{9}$ kg

Results: Calbuco

Near source cloud detected by MW-MMW and TIR-IR sensors, with instantaneous total mass estimations for Calbuco eruption occurred in 2015.





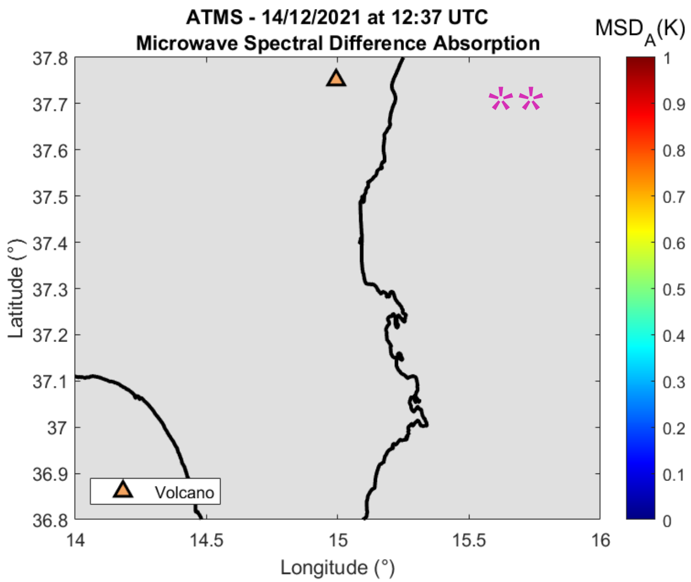


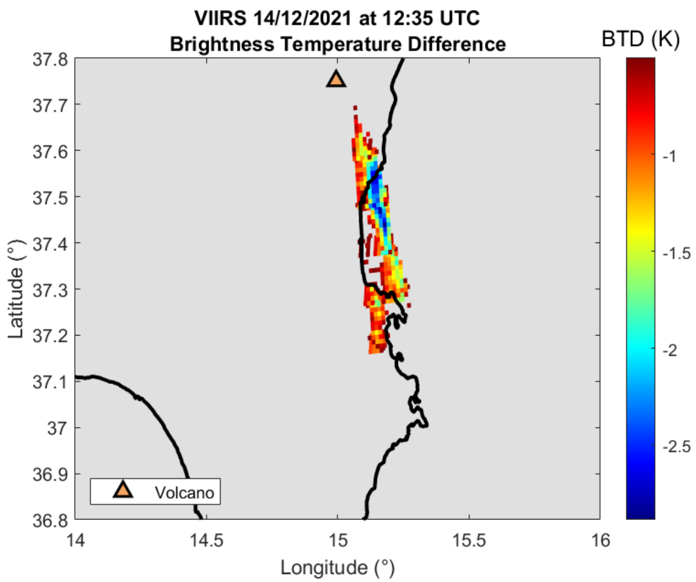
Sensor	EPR	MLE	NN
ATMS	$4.2e^{10}$ kg	$4.4e^{10}$ kg	$4.2e^{10}$ kg
VIIRS	✗	$4.10e^{7}$ kg*	$6.10e^{7}$ kg*

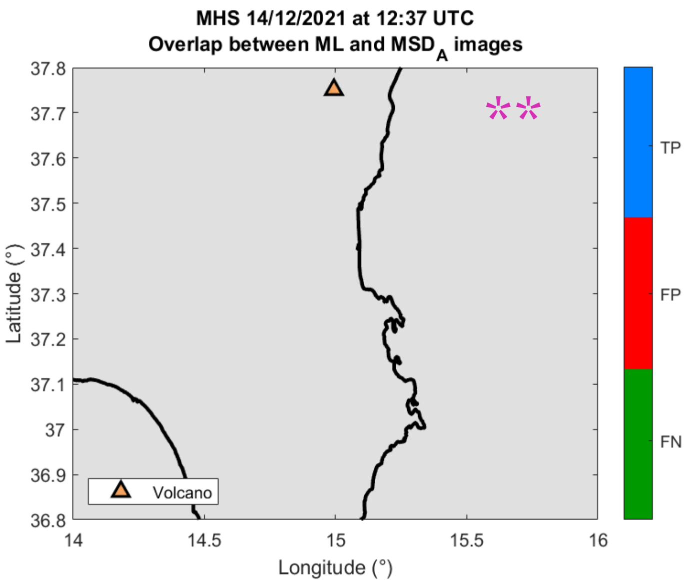
* only near source cloud

Results: Etna

Distal cloud by the TIR-IR sensor, with instantaneous total mass estimations for Etna eruption occurred in 2021.







Sensor	EPR	MLE	NN
ATMS	✗	✗	✗
VIIRS	✗	$2.58e^6$ kg	$3.00e^6$ kg

** cloud not detected

Conclusions & Beyond

Conclusions:

Detection:

- The BTD approach returns poor results in terms of proximal cloud detection.
- The MSD approach is particularly effective during the first stages of the eruption.
- RF proximal balances FP and FN and reduces thresholds dependence.

Retrieval:

- The MLE and NN estimates are in line with the parametric formula.

Beyond:

Detection:

- RF proximal approach identifies more classes: "ash on meteo", "ash on land", "ash on water”.
- RF proximal approach collects more data to consolidate the results .

Retrieval:

- Improve the RTM by:
  - considering the water vapour correction also for MW-MMW observations.
  - considering the volcanic particles of irregular shape.

Thanks

Credit: INGV-OE camera, Etna 14/12/2021 at 12:40 UTC