Volcanic cloud retrievals from satellite using multispectral data in the TIR. Algorithm description, error assessment and perspectives

S. Corradini

Istituto Nazionale di Geofisica e Vulcanologia (INGV) – Rome

INGV

1st SGF/ENS workshop
"Volcanic plumes: observation, modelling and impacts“
Paris, 25 November 2015

Etna, 26 October 2013
Credit: ***Boris Behncke, INGV-OE***

MEDiterranean SUpersite Volcanoes
MED-SUV

Overview

- **Introduction**
- **MODIS and SEVIRI multispectral satellite sensors**
- **Ash and SO_2 detection**
- **Ash and SO_2 retrievals**
    - LUT approach
    - VPR approach
- **Volcanic Ice detection and retrievals**
- **Sensitivity analysis**
- **Validation**
- **Conclusions**

Overview

- **Introduction**
- **MODIS and SEVIRI multispectral satellite sensors**
- **Ash and SO_2 detection**
- **Ash and SO_2 retrievals**
  - LUT approach
  - VPR approach
- **Volcanic Ice detection and retrievals**
- **Sensitivity analysis**
- **Validation**
- **Conclusions**

Volcanic Gas emissions

Particles

The term 'volcanic ash' refers to particles having dimensions varying between a few mm and less than 1 micron. The size, density and shape of the particles determine their residence time in the atmosphere. Typically particles with a radius greater than 100 μm have low residence times (from minutes to hours), while particles smaller than 10 μm and gaseous aerosols can stay in the atmosphere for weeks and travel for thousands of kilometers.

Etna volatile fluxes (1975-1995)

Specie	Etna mean (Gg/yr)	Global Volcanism (Gg/yr)	Etna/Global Volcanism	Etna/Global Natural
H_2O	$5.0 \cdot 10^5$	$5.0 \cdot 10^6$	10%	
CO_2	$1.3 \cdot 10^4$	$(8\text{-}20) \cdot 10^4$	(7-16)%	0.018%
SO_2	$2.0 \cdot 10^3$	$1.3 \cdot 10^4$	11%	0.68%
HCl	$4.8 \cdot 10^2$	$(4\text{-}110) \cdot 10^2$	9%	0.16%
HF	59	60-6000	8%	0.70%
Br	2	77	2.6%	0.19%
Zn	4.9	9.6	51%	0.9%
Cu	0.57	9.4	5.9%	≤ 1.0%
Mn	0.23	42	0.6%	0.013%
Pb	0.15	3.3	4.5%	1.25%
Mo	0.08	0.4	20%	2.8%
As	0.04	3.8	1.1%	0.33%
Se	0.018	0.95	1.9%	2%
Ni	0.036	3.8	1.0%	0.12%
Hg	0.027	1.0	2.7%	1.1%
Cd	0.050	0.82	6.1%	3.9%
Sr	0.007	15	0.05%	0.016%
Sb	0.004	0.71	0.56%	0.017%

[P. Allard, private Communication]

Impact of volcanic eruptions

- ***Health*** *[Horwell et al., 2006]*

✓ Ballistic missiles

✓ Lava flow and pyroclastic flows [gas mixtures, ash, pumice and rocks pushed by gravity downstream along the flanks of the volcano]

✓ Lahar [mudflow composed of pyroclastic material and water flowing down the slopes of a volcano]

✓ Ash/Gas emissions

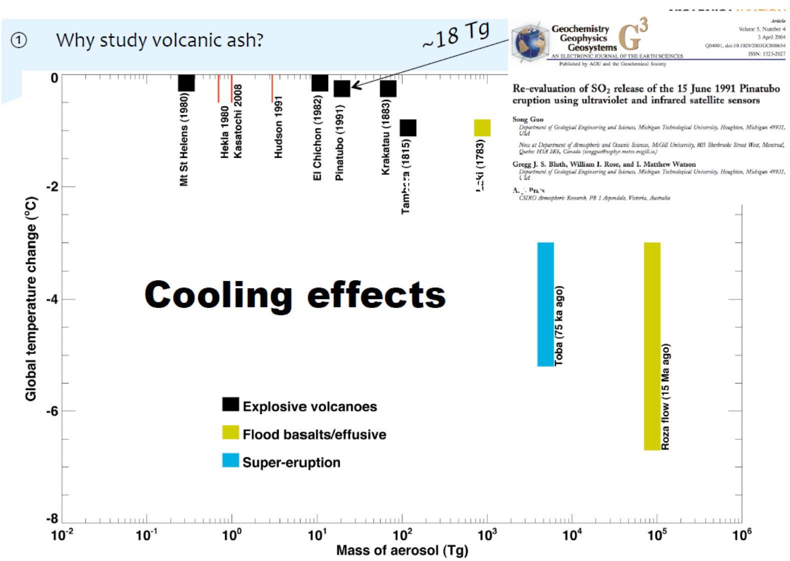
✓ Seismic activity, tsunamis

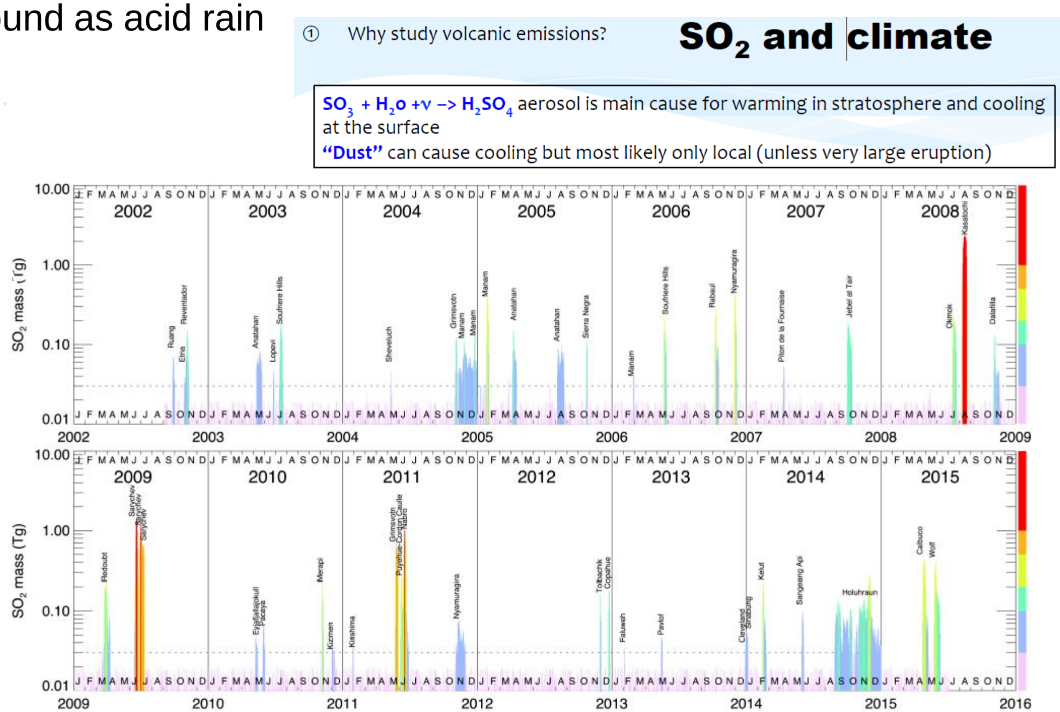
Environment

[Thordasson et al., 2003; Grainger et al., 2003; Guo et al., 2004]

Volcanic eruptions can have a high impact on the environment by altering the climate:

- ✓ Large eruptions lead gas and ash into the atmosphere which may remain for several years. The main effect is to reflect solar radiation causing a net cooling effect
- ✓ Aerosols promote ozone destruction. In the troposphere, these aerosols may act as nuclei for the cirrus cloudy formation, further interfering with the irradiation of the Earth
- ✓ The majority of the SO_2 is converted into sulfuric acid which condenses into fine particulate. These sulfur aerosols reflect solar radiation, cooling the troposphere, and absorb heat from the earth, warming the stratosphere
- ✓ CO_2 is a greenhouse gas and contributes to global warming
- ✓ HCl and HF are soluble and fall to the ground as acid rain





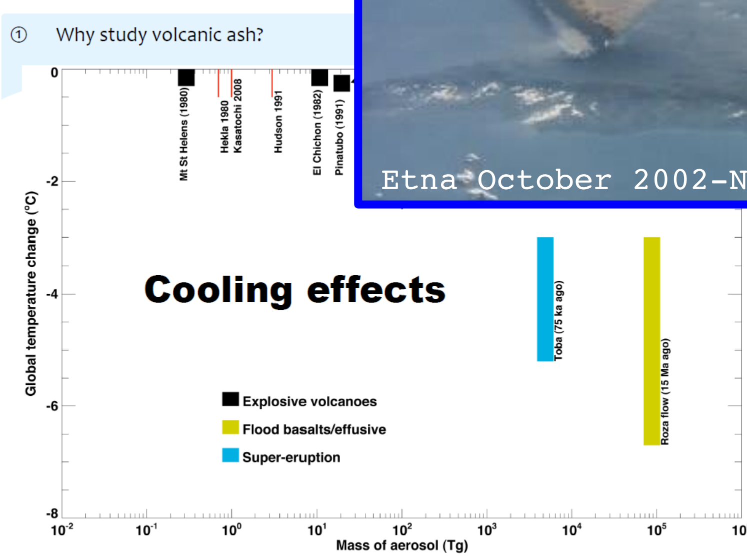
Courtesy from F. Prata

Environment

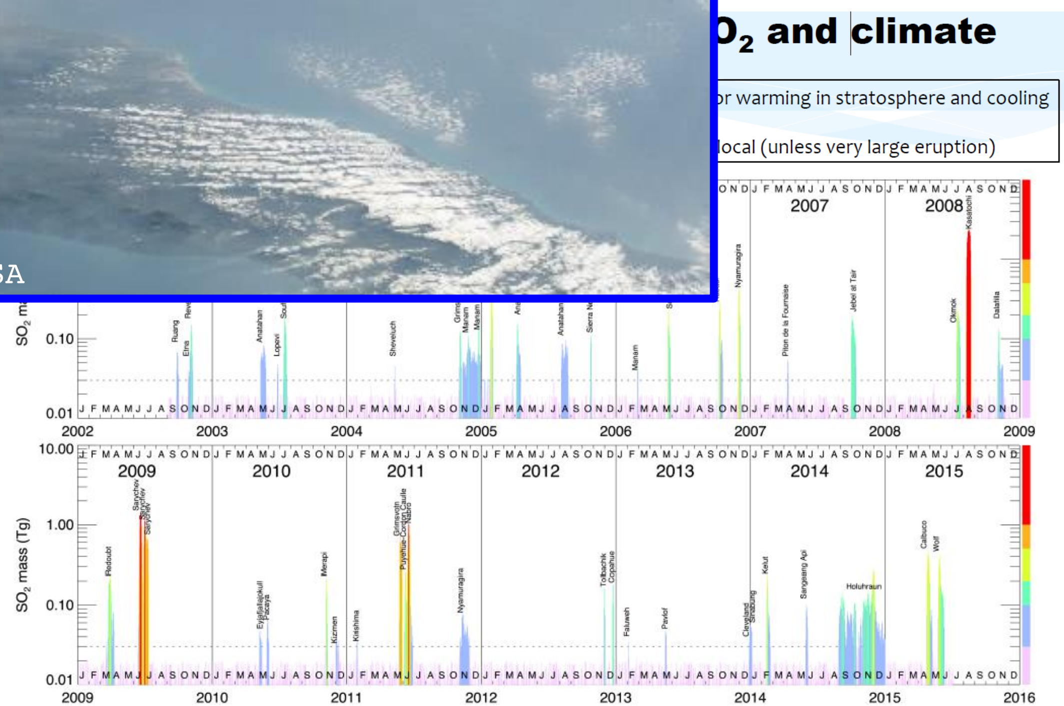
[Thordasson et al., 2003; Grainger et al., 2003; Guo et al., 2004]

Volcanic eruptions can have a high impact on the environment by altering the climate:

- ✓ Large eruptions … years. The main effect is to refle…
- ✓ Aerosols promo… nuclei for the cirrus cloudy formatio…
- ✓ The majority of … culate. These sulfur aerosols reflect … rth, warming the stratosphere
- ✓ CO_2 is a greenh…
- ✓ HCl and HF are…

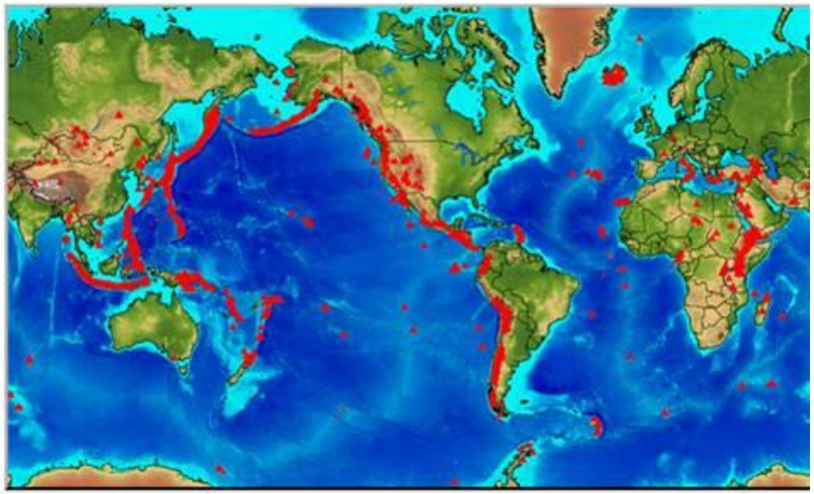


Courtesy from F. Prata



- ***Air flight*** *[Casadevall, 1994; Prata, 2009; Zehner, 2012; Prata and Prata, 2015]*

  - ✓ Loss of engine power
  - ✓ Engine shutdown turbine
  - ✓ Abrasion of turbine blades
  - ✓ Abrasion of the windows and windscreen
  - ✓ Abrasion of the fuselage



Encounter Severity Index

Description	Severity Class	Number
engine failure or other damage leading to crash	5	0
temporary engine failure	4 *(engine failure)*	9
engine vibration and "surging"; engine damage	3	17
heavy cabin dust; exterior abrasion; deposition of ash in engines	2	53
light dust in cabin; engine temp. fluctuate but remain "normal"	1	12
sulfur odor and anomalous haze	0	23
	Lacking data	15
	Total incidents reported	129

Courtesy from T. Casadevall

15 December 1989
Volcanic ash cloud coming from Mt. Redoubt volcano (Alaska)
Boeing 747 (KLM Flight 867) with 231 passengers on board.
Power loss and all four engines.

7 June, 2011
San Carlos de Bariloche Argentina (airport)

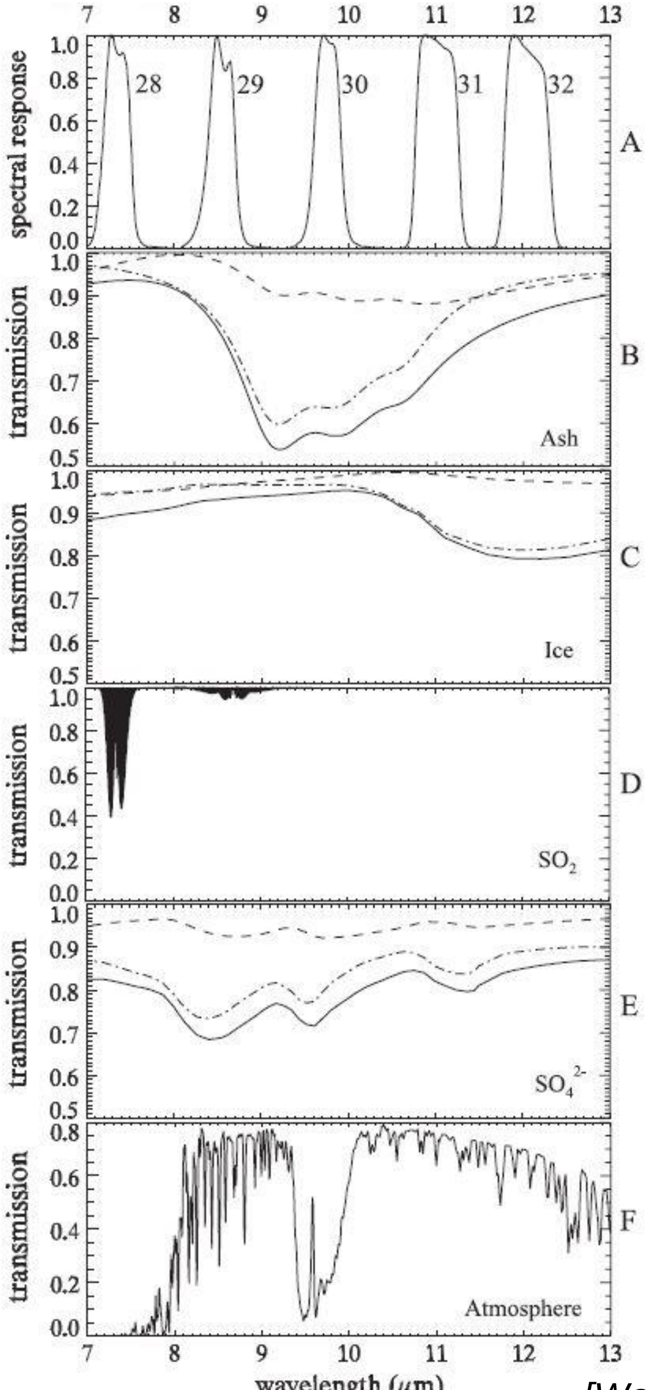
Reventedor ashfall at Quito airport, Ecuador Oct. 1999

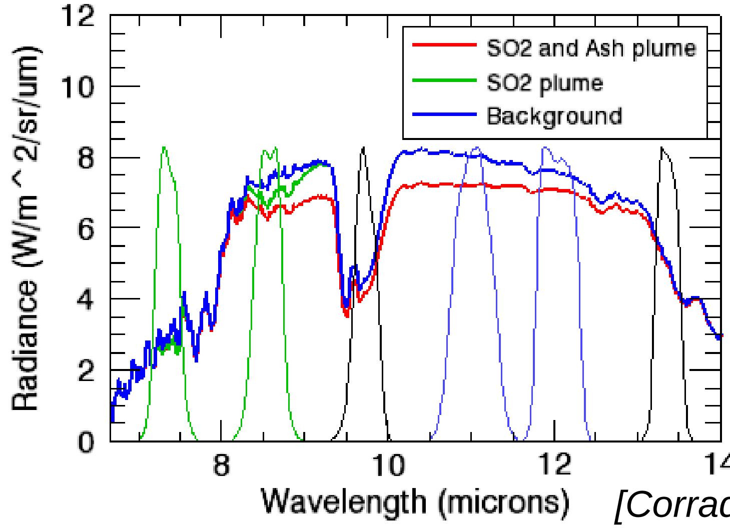
Courtesy from T. Casadevall

Feb. 2014 Kelut ashfall at Yogyakarta airport, Indonesia

Courtesy from T. Casadevall

Particles and gases absorption in the TIR spectral range





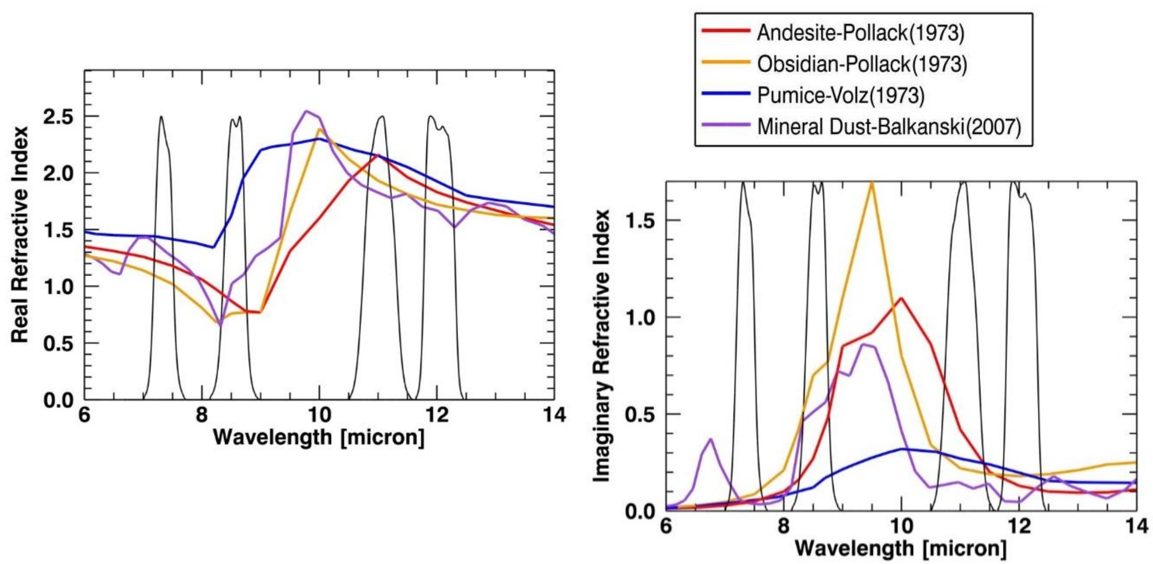
MODTRAN simulation:

Ts=292K , ε = 0.99, Hp=5000m , tp=1000 m

SO_2=5 gm^{-2}

τ=1 , Re=2.34μm

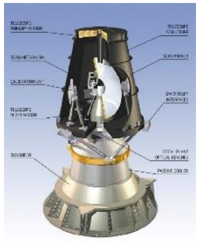
[Corradini et al., AMT, 2009]



[Watson et al., JVGR, 2004]

Overview

- Introduction
- **MODIS and SEVIRI multispectral satellite sensors**
- Ash and SO_2 detection
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- Validation
- Conclusions



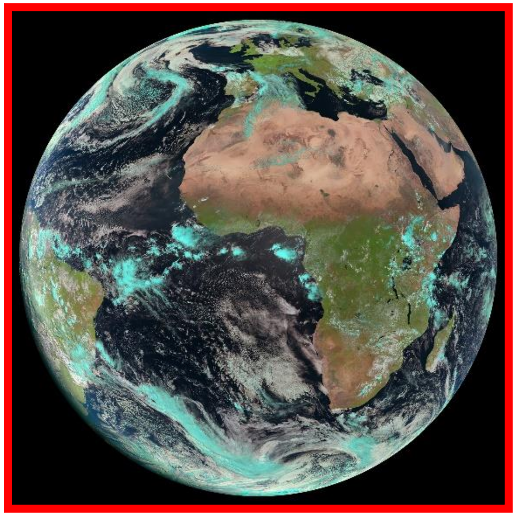
Spinning Enhanced Visible and Infrared Imager (SEVIRI)

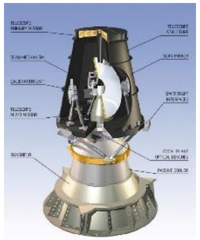
Channel No	Central Wavelength (μm)	Spatial Resolution (km)	Temporal Resolution (min)	
1	0.6	3	15	
2	0.8	3	15	
3	1.6	3	15	
4	3.9	3	15	
5	6.2	3	15	
6	7.3	3	15	SO_2
7	8.7	3	15	
8	9.7	3	15	
9	10.8	3	15	Ash
10	12	3	15	
11	13.4	3	15	
12 (HRV)	0.8	1	15	

Current Meteosat Satellites

SATELLITE	LIFETIME	POSITION	SERVICES
MSG-4	15/07/2015 – tbc	In orbit storage	n/a
Meteosat-10 (MSG)	05/07/2012 – Nominal fuel lifetime is until 2022	0°/36,000 km	0º SEVIRI Image Data. Real-time Imagery. Data Collection Service
Meteosat-9 (MSG)	22/12/2005 – Fuel lifetime is expected to be extended until 2021	9.5° E/36,000 km	Rapid Scan Service from 9 April 2013. Real-time Imagery
Meteosat-8 (MSG)	28/08/2002 – Fuel lifetime is expected to be extended until 2019	3.5° E/36,000 km	Backup service for 0°, plus RSS from 9 April 2013
Meteosat-7 (MFG)	02/09/1997 (IODC since 01/11/2006) – 2016	57° E/36,000 km	Indian Ocean Coverage. Real-time Imagery. Date Collection Service

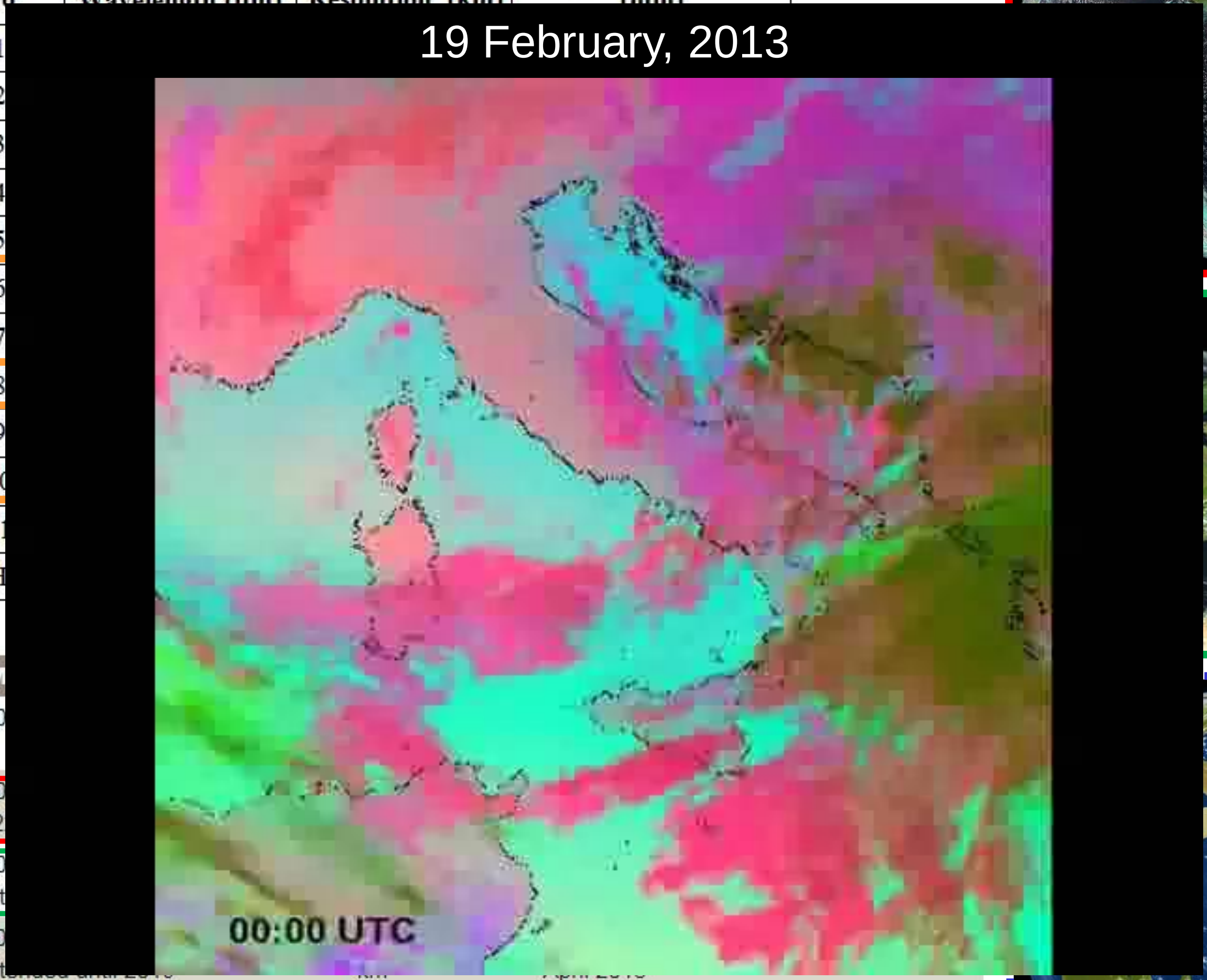
http://www.eumetsat.int/website/home/Satellites/index.html



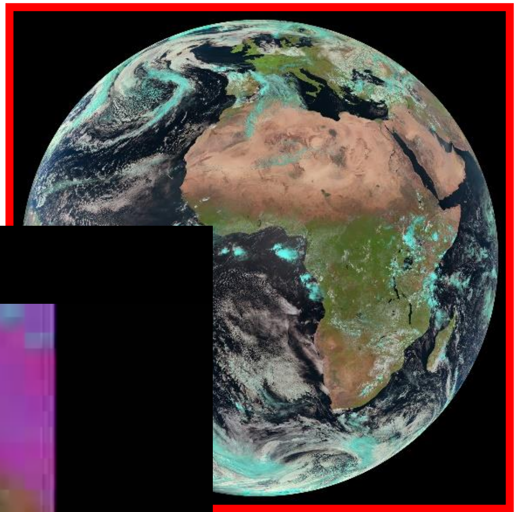


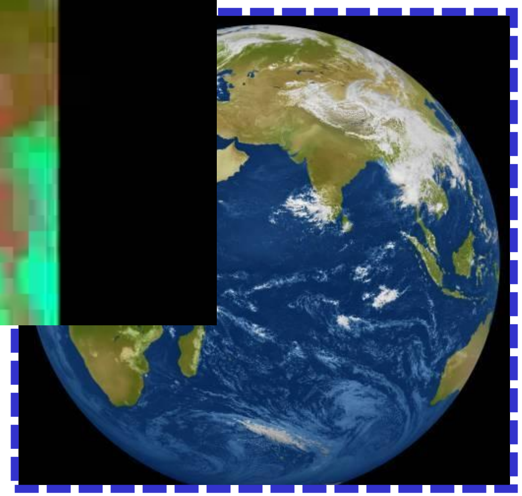
Spinning Enhanced Visible and Infrared Imager (SEVIRI)

Channel No.	Central Wavelength (µm)	Spatial Resolution (km)	Temporal Resolution (min)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12 (H…			



SATELLITE	LIFETIM…		
MSG-4	15/07/20…		
Meteosat-10 (MSG)	05/07/20… until 202…		
Meteosat-9 (MSG)	22/12/20… to be ext…		
Meteosat-8 (MSG)	28/08/20… to be ext… until 2016	km	April 2013
Meteosat-7 (MFG)	02/09/1997 (IODC since 01/11/2006) – 2016	57° E/36,000 km	Indian Ocean Coverage. Real-time Imagery. Date Collection Service





http://www.eumetsat.int/website/home/Satellites/index.html

MODIS

http://modis.gsfc.nasa.gov/

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	
	4	545 - 565	29.0	
	5	1230 - 1250	5.4	
	6	1628 - 1652	7.3	
	7	2105 - 2155	1.0	
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	
	9	438 - 448	41.9	
	10	483 - 493	32.1	
	11	526 - 536	27.9	
	12	546 - 556	21.0	
	13	662 - 672	9.5	
	14	673 - 683	8.7	
	15	743 - 753	10.2	
	16	862 - 877	6.2	
Atmospheric Water Vapor	17	890 - 920	10.0	
	18	931 - 941	3.6	
	19	915 - 965	15.0	

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[delta]T(K)[4]	
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05	
	21	3.929 - 3.989	2.38(335K)	2.00	
	22	3.929 - 3.989	0.67(300K)	0.07	
	23	4.020 - 4.080	0.79(300K)	0.07	
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25	
	25	4.482 - 4.549	0.59(275K)	0.25	
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)	
	27	6.535 - 6.895	1.16(240K)	0.25	
	28	7.175 - 7.475	2.18(250K)	0.25	SO_2
Cloud Properties	29	8.400 - 8.700	9.58(300K)	0.05	SO_2
Ozone	30	9.580 - 9.880	3.69(250K)	0.25	
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05	Ash
	32	11.770 - 12.270	8.94(300K)	0.05	Ash
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25	
	34	13.485 - 13.785	3.76(250K)	0.25	
	35	13.785 - 14.085	3.11(240K)	0.25	
	36	14.085 - 14.385	2.08(220K)	0.35	

MODIS on board the NASA-Terra & NASA-Aqua satellites

Launch Date: December 18,1999
Equatorial crossing: 10:30 a.m. descending node

Launch Date: May 4, 2002
Equatorial crossing: 1:30 p.m. ascending node

Altitude	705 km
Inclination	99°
Period	99 minutes (16 orbits per day)
Orbit	Sun synchronous, near polar orbit
Mapping	1-2 days
Swath Width	230 km
Spatial Res.	1 km (TIR-nadir)

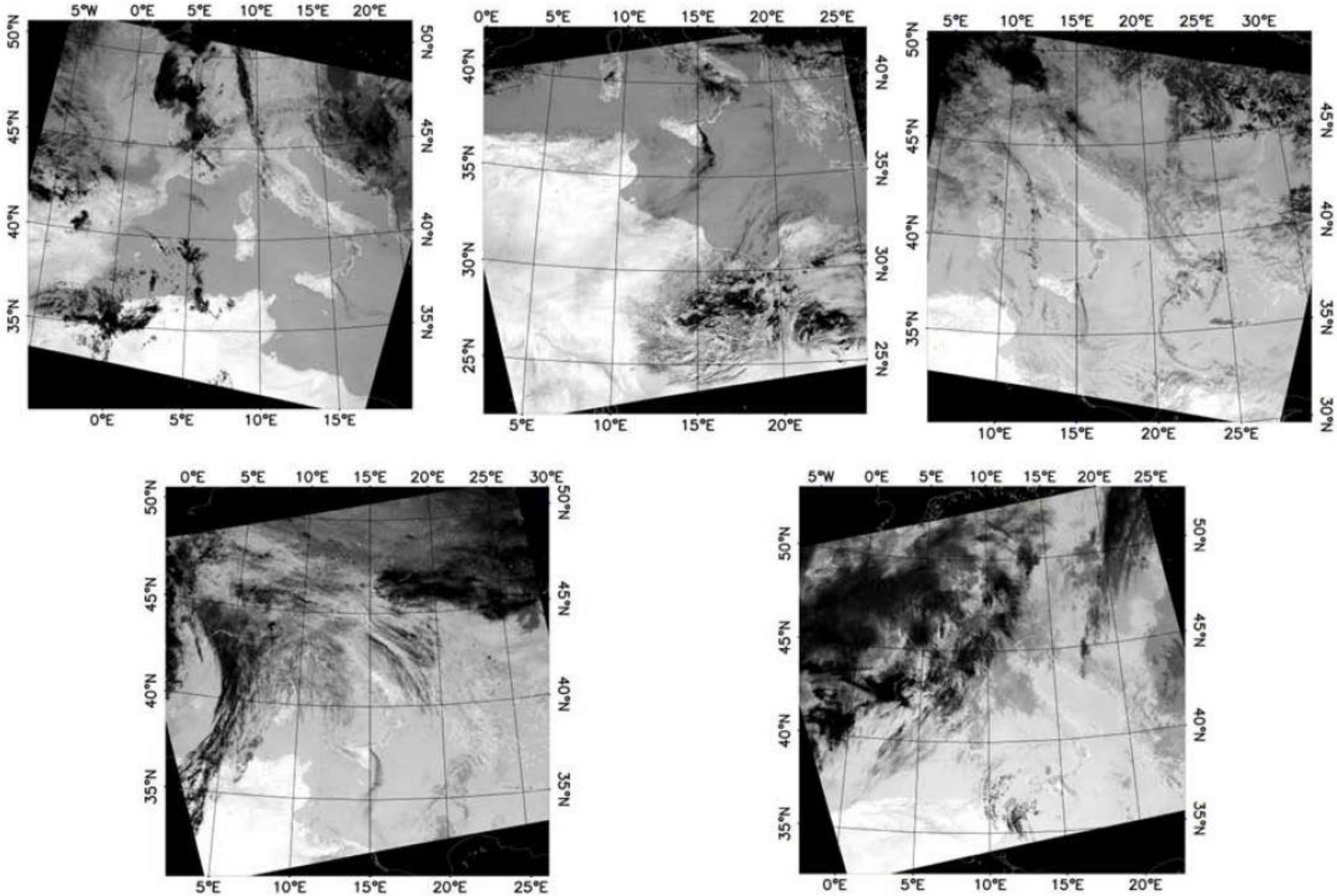


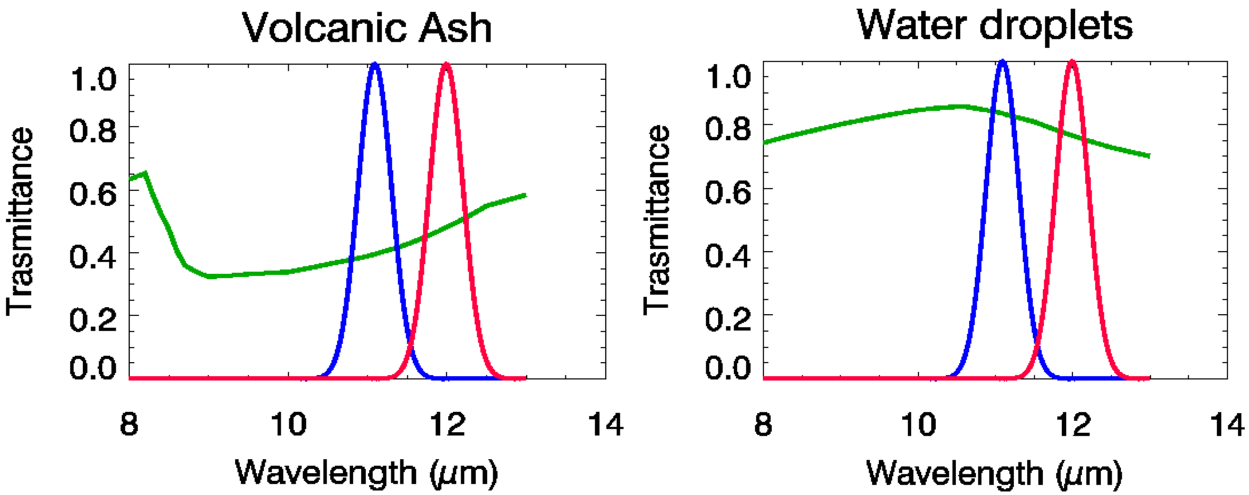
Fig. 1. Channel 31 MODIS test case images. Top Plates, from left to right: 23 July 2001 at 10:35 UTC; 28 October 2001 at 12:15 UTC and 29 October 2002 at 12:05 UTC. Bottom Plates, from left to right: 30 October 2002 at 9:45 UTC and 24 November 2006 at 12:20 UTC.

Overview

- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- **Ash and SO_2 detection**
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- Validation
- Conclusions

Ash Detection, the BTD approach *[Prata, 1989]*

The **BTD** (Brightness Temperature Difference) technique is based on the different absorption of ash and ice/water droplets in the channels centered at 11 and 12 μm



BTD = T_b(11 μm) - T_b(12 μm)

T_b(11 μm) - T_b(12 μm) < α (<0)

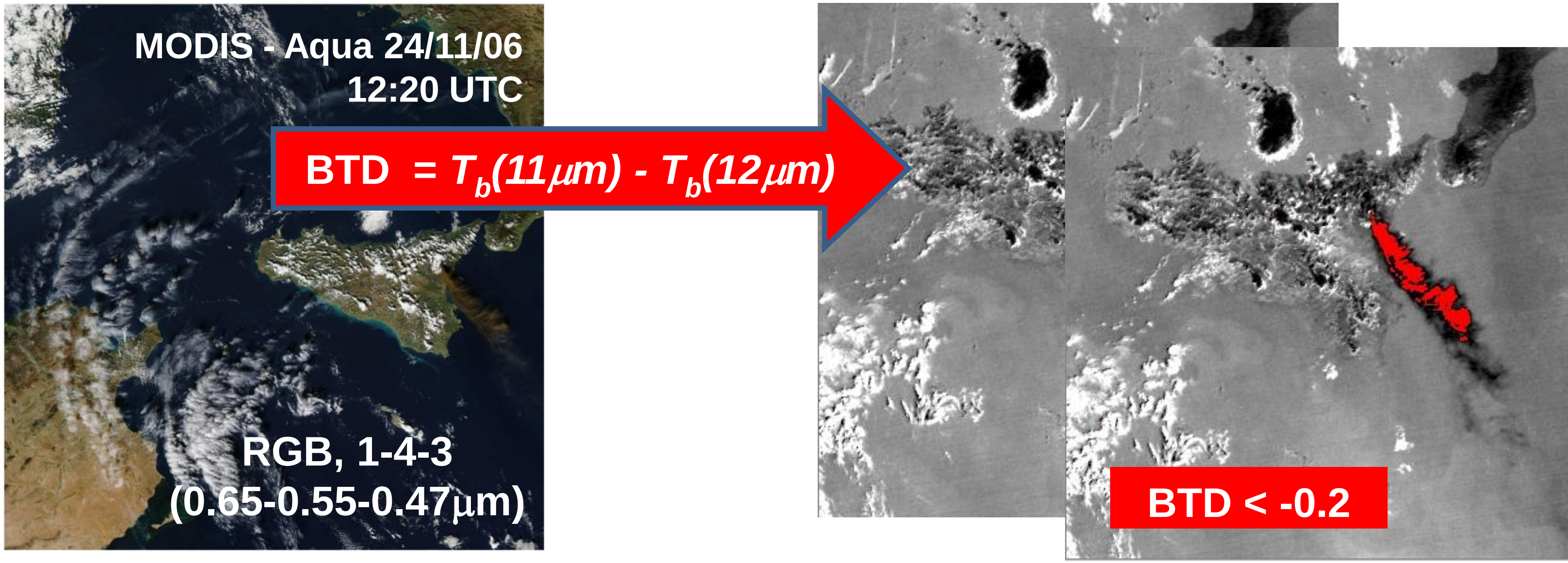
T_b(11 μm) - T_b(12 μm) > β (>0)

- **Advantages:**

- Very simple application

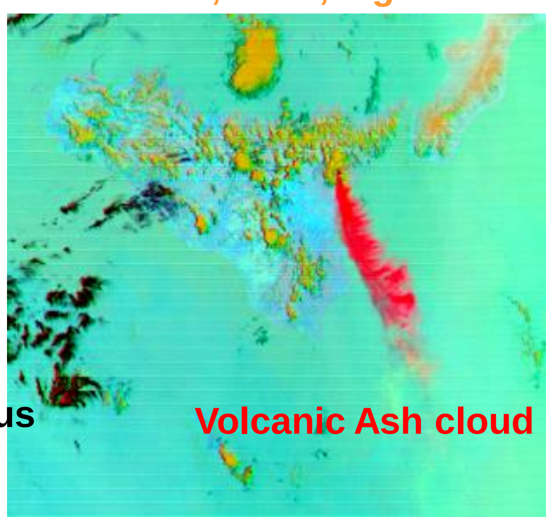
- **Drawbacks (where the procedure fails)** *[Prata et al., 2002]***:**

- Over land surfaces during night;
- In the presence of high content of water vapour;
- On soils containing high amounts of quartz (deserts);
- On very cold surfaces (temperatures below 220 K);
- On surfaces covered by ice.



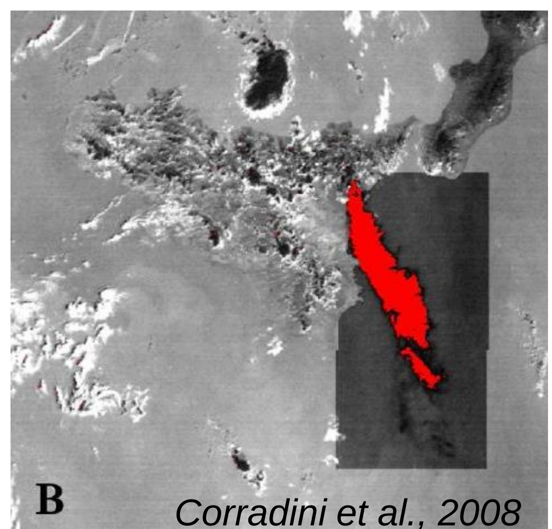
- **Red-Green-Blue (RGB) composite image**
  [Millington et al., 2012]

R: $T_b(12\ \mu m) - T_b(11\ \mu m)$
G: $T_b(11\ \mu m) - T_b(8.7\ \mu m)$
B: $T_b(10.8\ \mu m)$



Modified BTD approaches

- **Atmospheric water vapour correction**
  [Prata et al., 2001; Yu et al., 2002; Corradini et al., 2008]



$BTD^* = BTD - BTD^w$

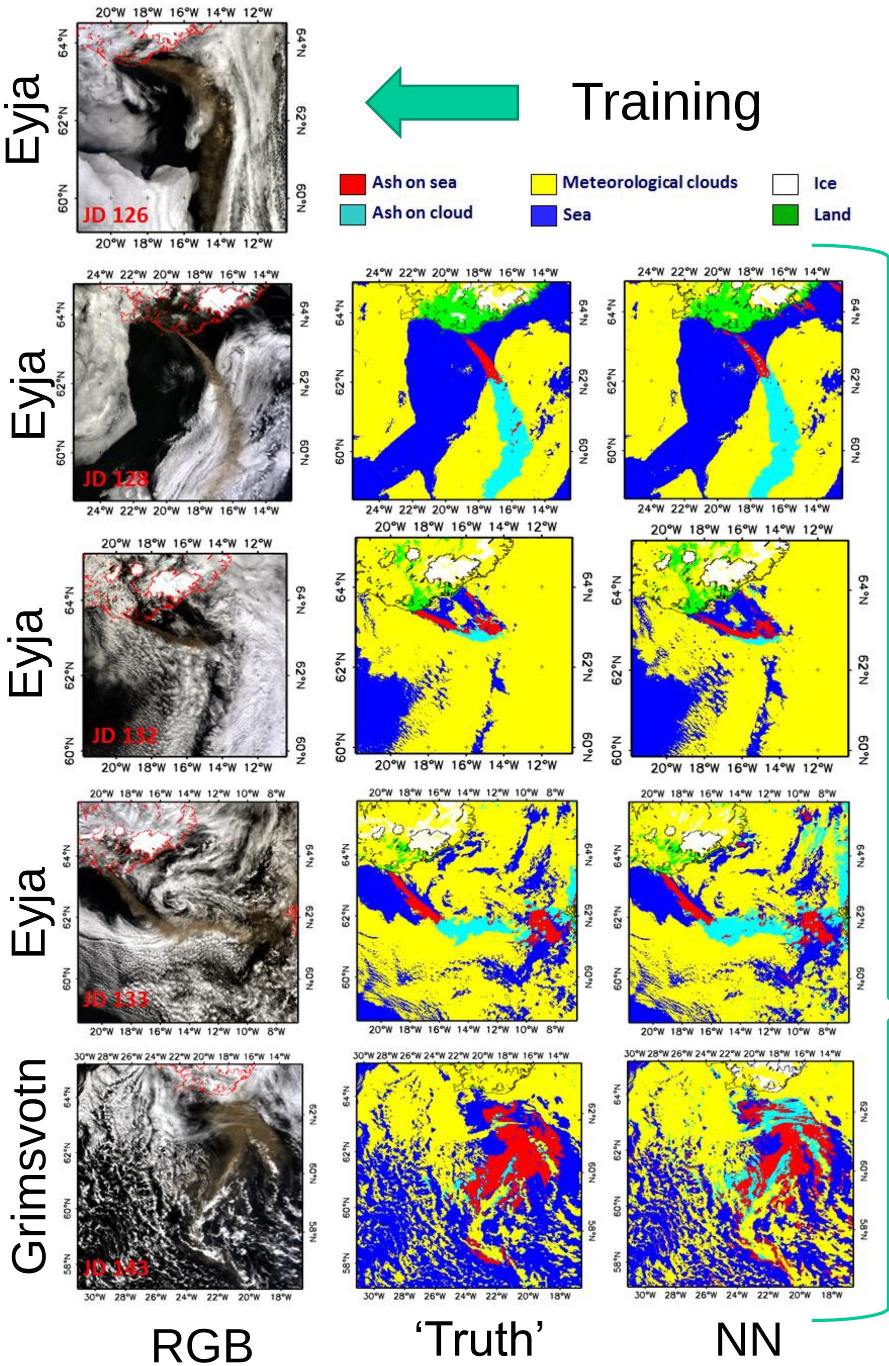
$BTD^w > 0$

3069 pixels

1292 pixels

• Ash Detection by using Neural Network approach

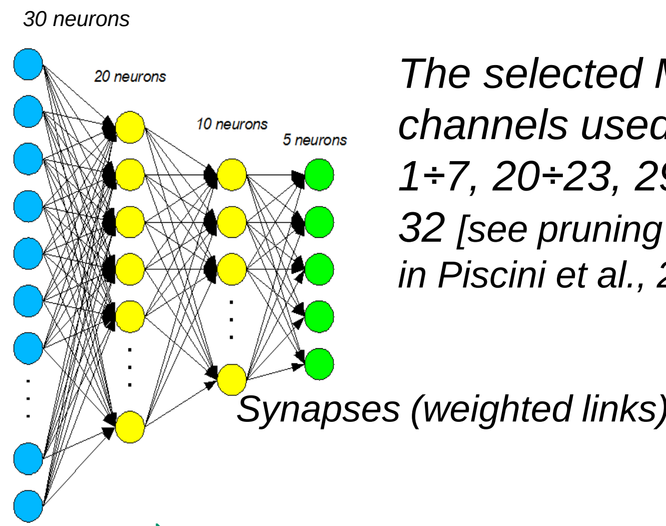
[Picchiani et al. 2014]



The NN has been trained using:

- ➢ *BTD approach*
- ➢ *MODIS L1 Land/Sea Mask*
- ➢ *MODIS L2 Cloud Products*
- ➢ *Threshold on MODIS band 7 for ice surfaces*

Multilayer Perceptron (MLP) NN *[Bishop, 1995]*



The selected MODIS channels used are: 1÷7, 20÷23, 29, 31 and 32 [see pruning analysis in Piscini et al., 2014].

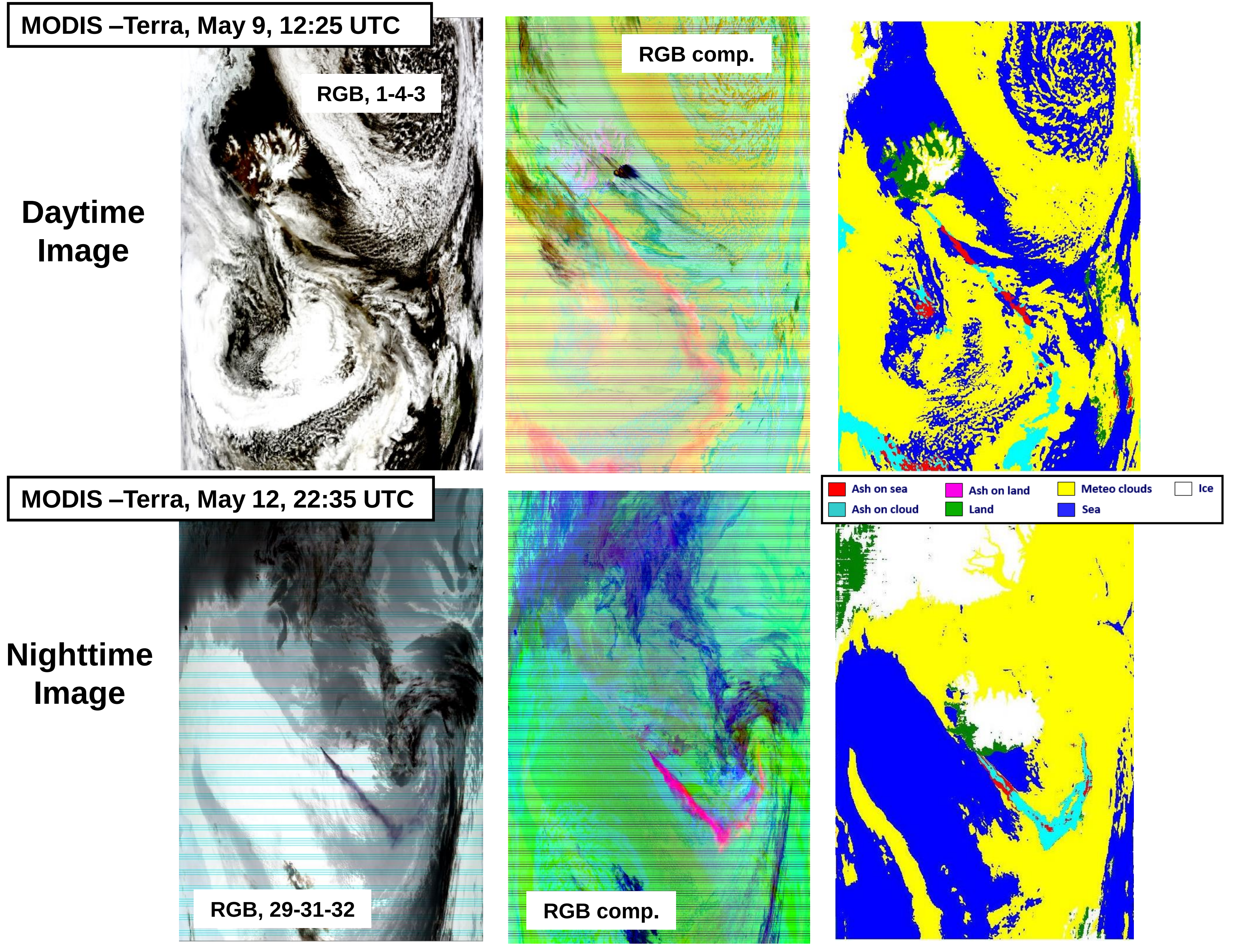
Validation

Improvements:

➢ application of a smoothing filter to avoid stripe noise

➢training of a new neural networks for the nighttime images

➢new class: ash on land

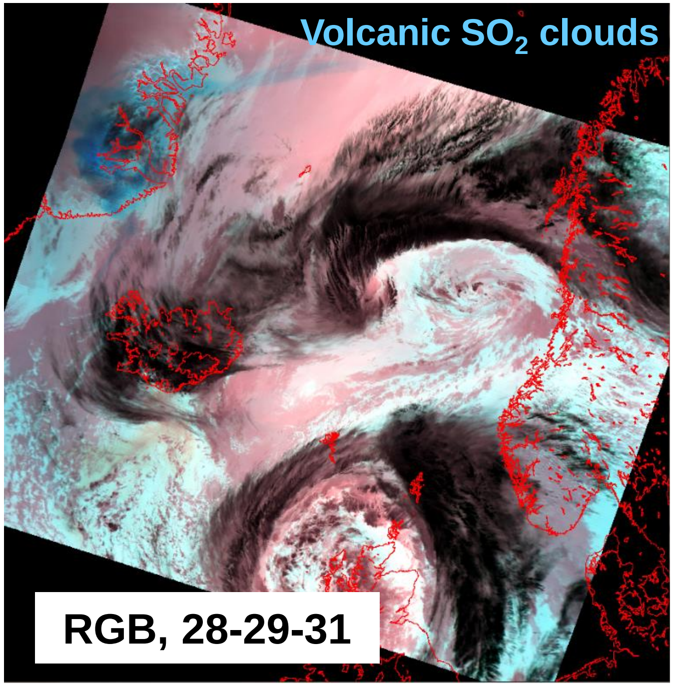


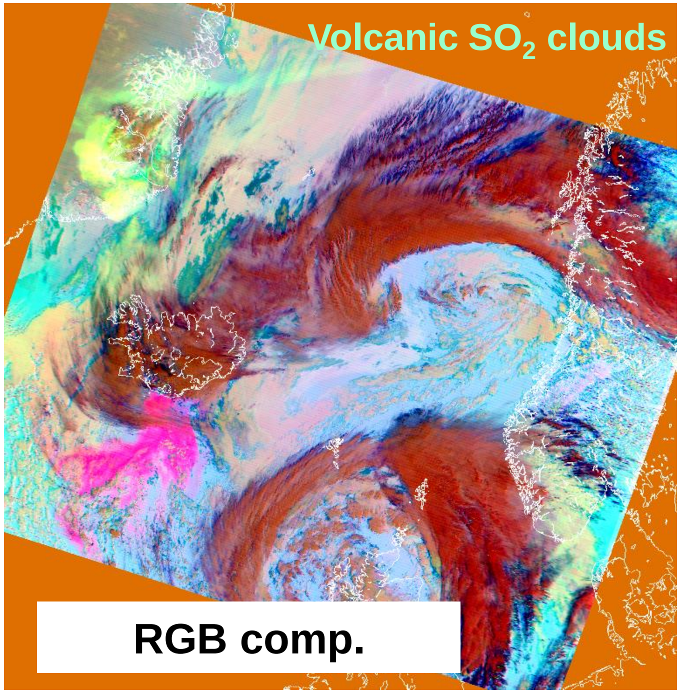
MODIS –Terra, May 9, 12:25 UTC
Daytime Image
RGB, 1-4-3
RGB comp.
MODIS –Terra, May 12, 22:35 UTC
Nighttime Image
RGB, 29-31-32
RGB comp.
Ash on sea
Ash on land
Meteo clouds
Ice
Ash on cloud
Land
Sea

SO_2 detection

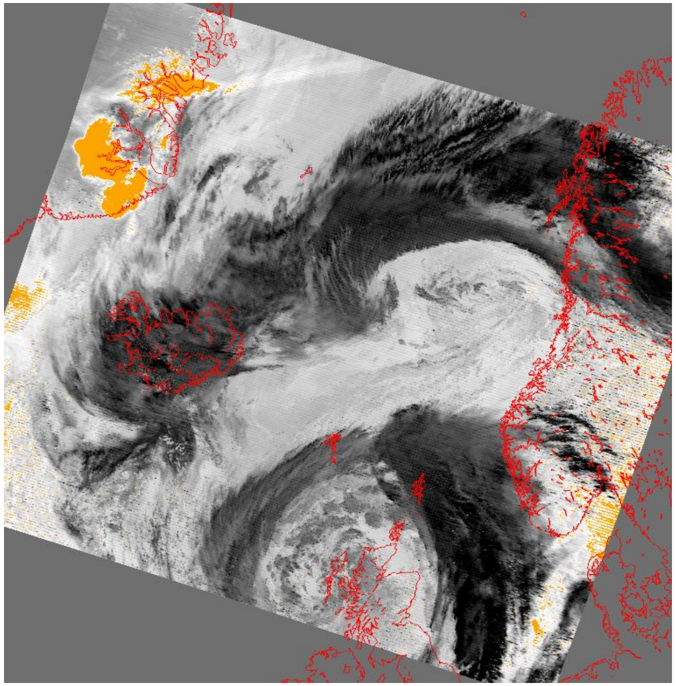
Grimsvotn (Iceland) 2011 eruption

MODIS-Terra, 23 May, 13:45 UTC





$BTD^+ = T_b(11\ \mu m) - T_b(8.7\ \mu m)$



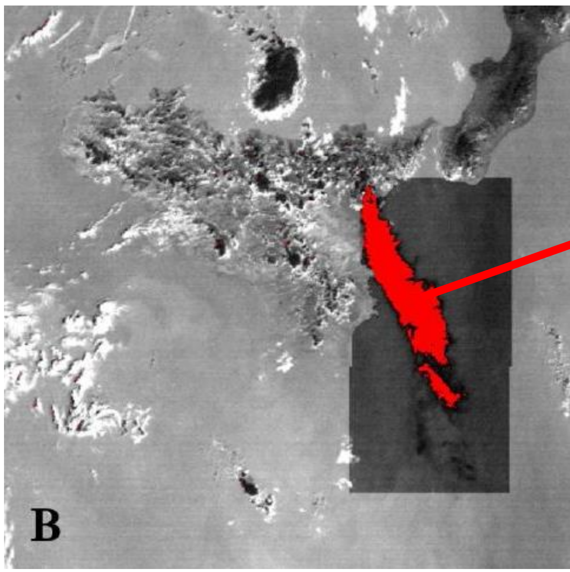
Overview

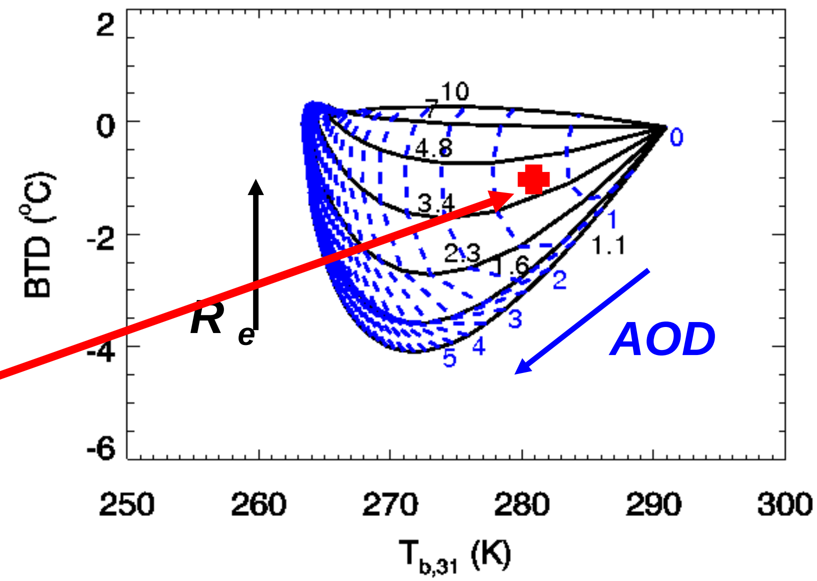
- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- **Ash and SO_2 retrievals**
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- Validation
- Conclusions

The Look Up Tabel (LUT) approach: Ash retrievals

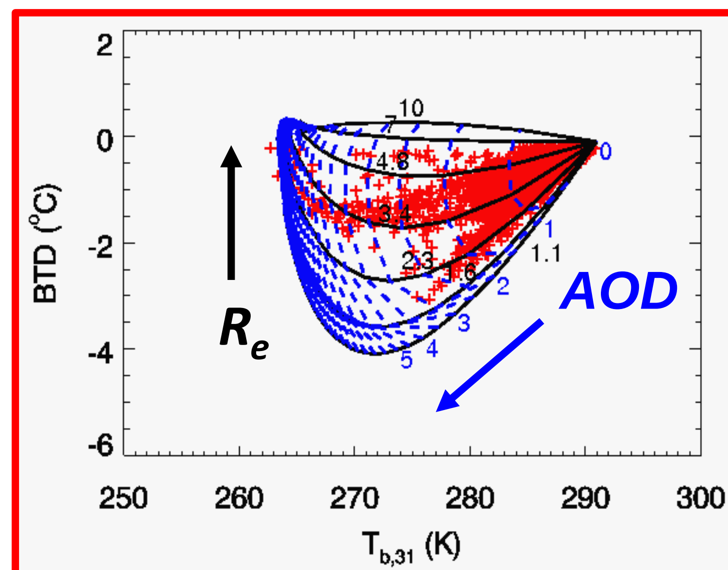
[Prata, 1989; Wen and Rose, 1994; Yu et al., 2002; Corradini et al., 2008; 2009; 2010]

✓ The ash retrievals are based on computing the simulated inverted arches curves "$BTD - T_b(11\mu m)$" varying AOD and effective radius (R_e)





$$M_{(m,n)} = \frac{4}{3} S_{(m,n)} \rho \frac{R_{e(m,n)} AOD_{(m,n),\lambda}}{Q_{ext,\lambda}(R_e)}$$



✓ The simulated inverted arches curves are computed using Radiative Transfer Models (RTM)

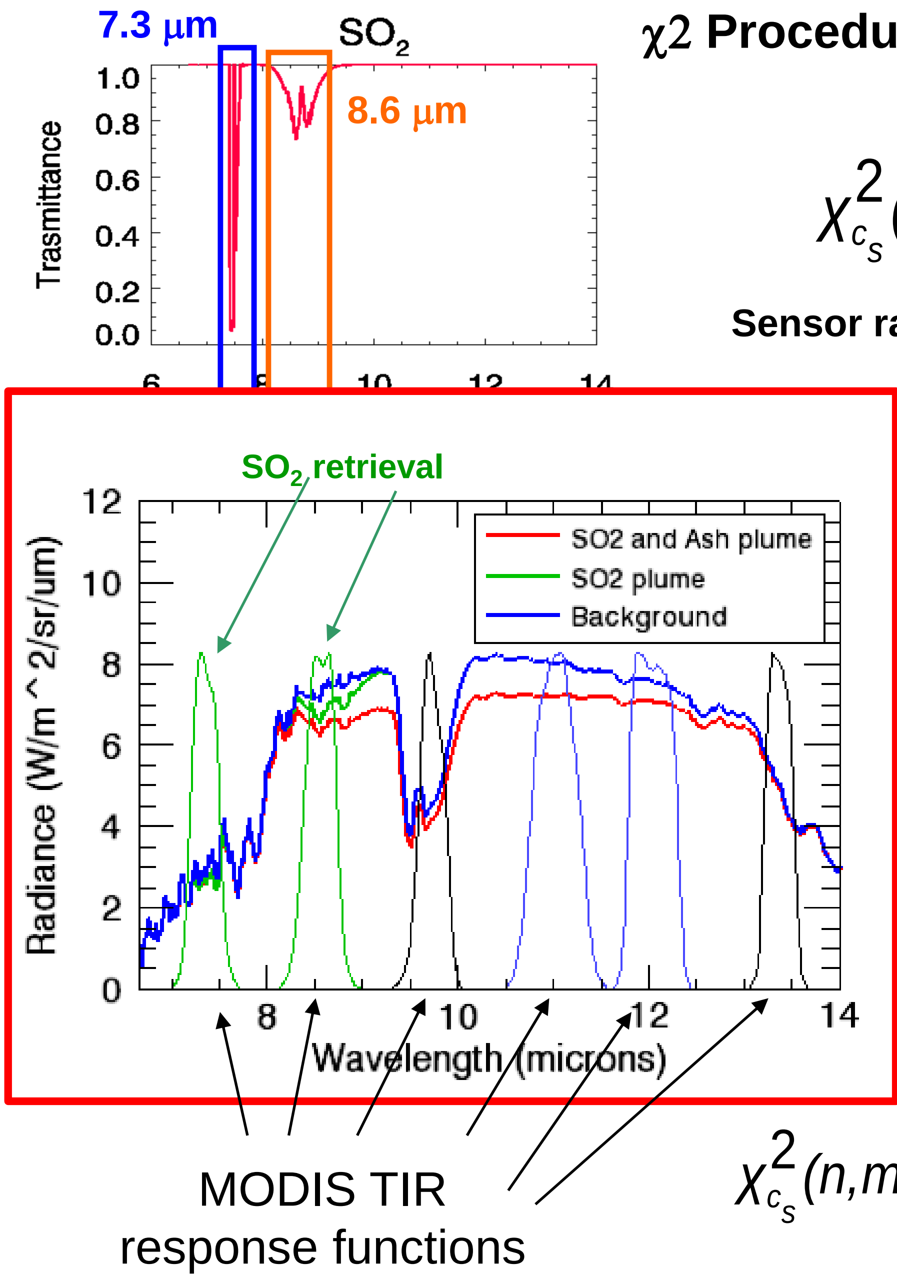
SO_2 retrieval

$\chi 2$ Procedure [*Realmuto et al., JGR, 1994; Teggi et al., JGR, 1999*]

$$\chi^2_{c_S}(n,m) = \sum_{i=1}^{n} \left[\frac{L^S_{(n,m),i} - L^M_{(n,m),i}(c_{s,j})}{L^S_{(n,m),i}} \right]^2 w_i$$

Sensor radiance

Simulated radiance (using RTM)

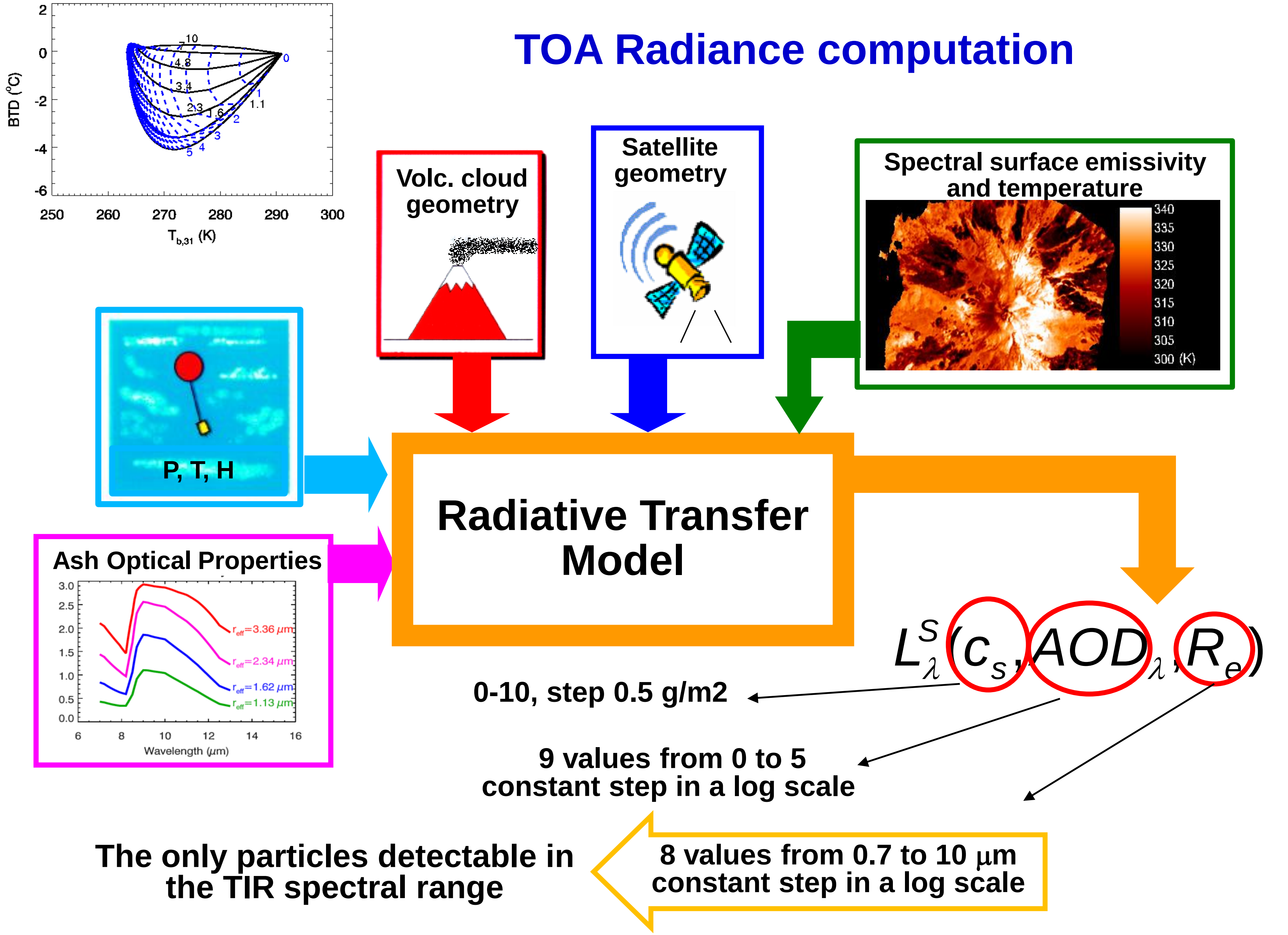


Ash effect on SO_2 retrieval

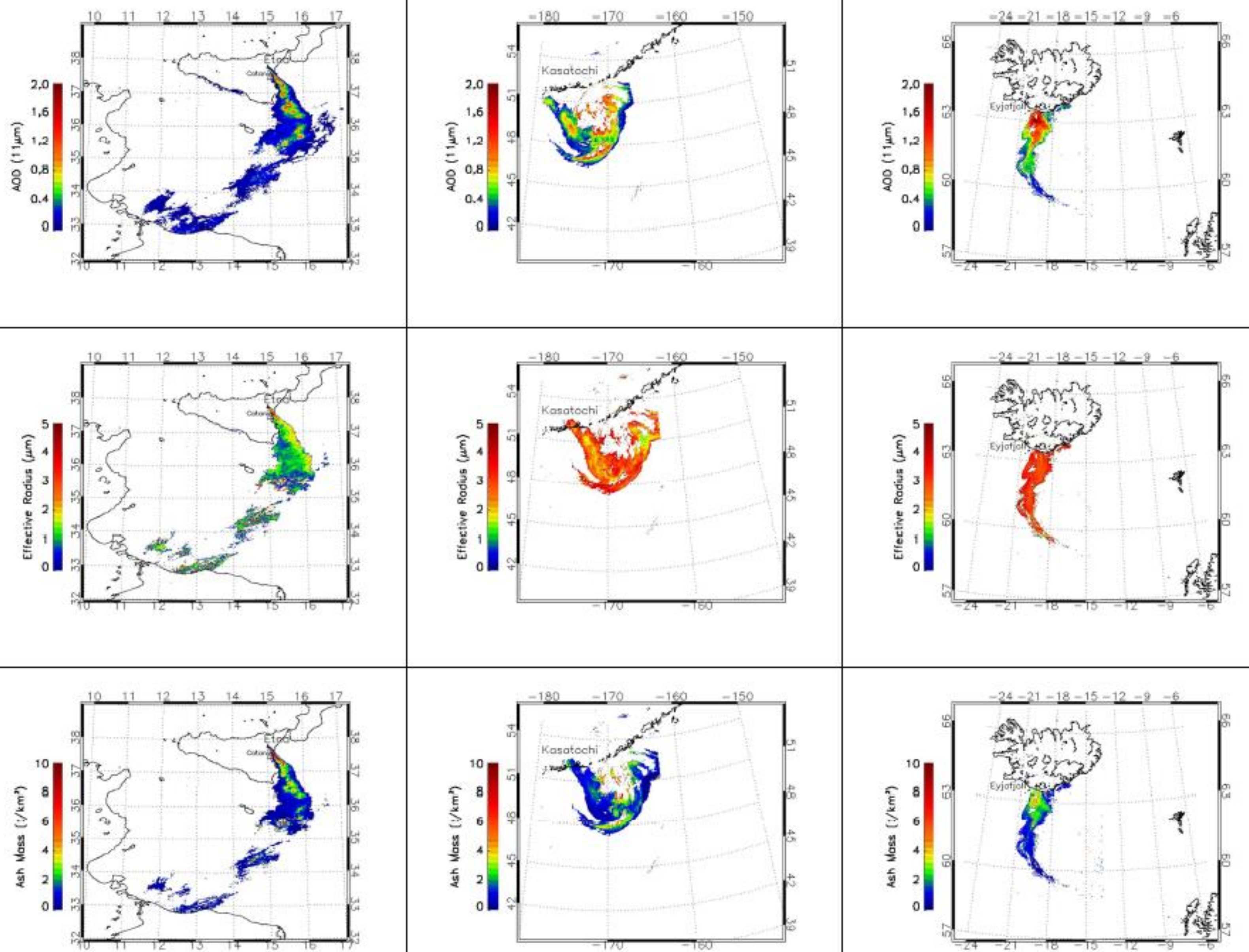
- During an eruption generally ash and gases are emitted simultaneously
- The plume ash particles reduce the top of atmosphere radiance in the entire TIR spectral range, including the channels used for the SO_2 retrieval
- The net effect is a significant SO_2 overestimation

[Corradini et al., AMT, 2009; Kearney and Watson, JGR, 2009]

$$\chi^2_{c_S}(n,m) = \sum_{i=1}^{n} \left[\frac{L^S_{(n,m),i} - L^M_{(n,m),i}(c_{s,j}, AOD_{(n,m)}, R_{e(n,m)})}{L^S_{(n,m),i}} \right]^2 w_i$$


TOA Radiance computation
2
0
-2
-4
-6
BTD (°C)
250
260
270
280
290
300
$T_{b,31}$ (K)
Volc. cloud geometry
Satellite geometry
Spectral surface emissivity and temperature
340
335
330
325
320
315
310
305
300 (K)
P, T, H
Radiative Transfer Model
Ash Optical Properties
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6
8
10
12
14
16
Wavelength (μm)
r_{eff}=3.36 μm
r_{eff}=2.34 μm
r_{eff}=1.62 μm
r_{eff}=1.13 μm
$L^S_\lambda(c_s, AOD_\lambda, R_e)$
0-10, step 0.5 g/m2
9 values from 0 to 5
constant step in a log scale
8 values from 0.7 to 10 μm
constant step in a log scale
The only particles detectable in the TIR spectral range

Etna (Italy) 2002	Kasatochi (Alaska) 2008	Eyjafjalla (Iceland) 2010
MODIS-Aqua	MODIS-Aqua	MODIS-Terra
28 October 2002, 12:00 UTC	9 August 2008, 00:50 UTC	19 April 2010, 14:55 UTC



[Corradini et al., 2011] *[Corradini et al., 2010]* *[SAVAA project, http://savaa.nilu.no/]*

Overview

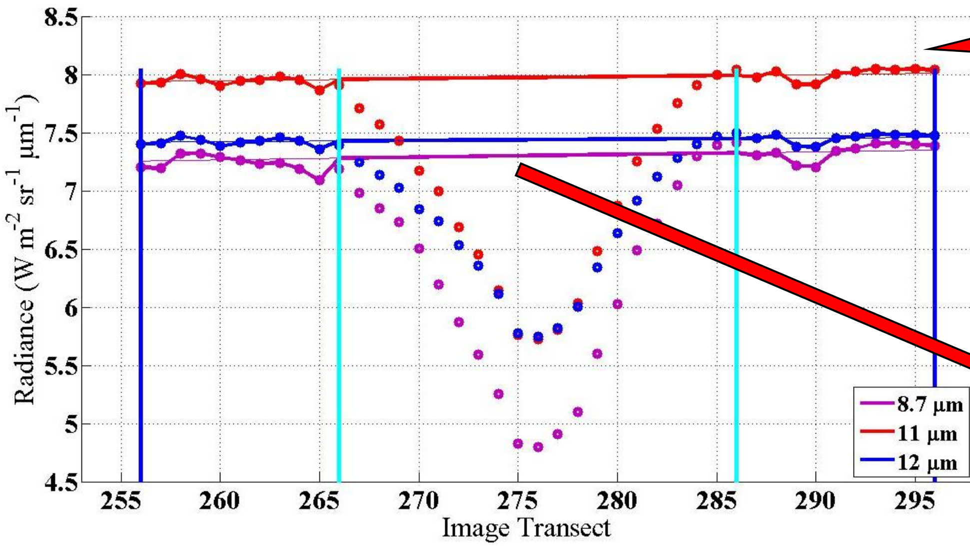
- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- **Ash and SO_2 retrievals**
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- Validation
- Conclusions

The Volcanic Plume Removal (VPR) procedure

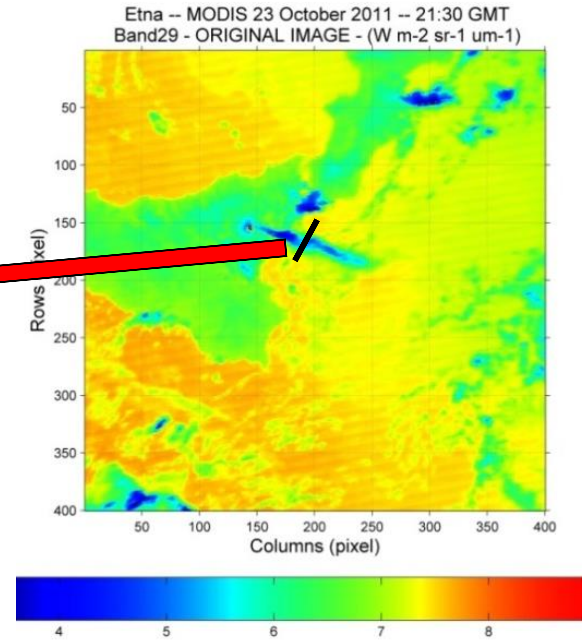
[Pugnaghi et al., AMT, 2013; Guerrieri et al., JVGR, 2015]

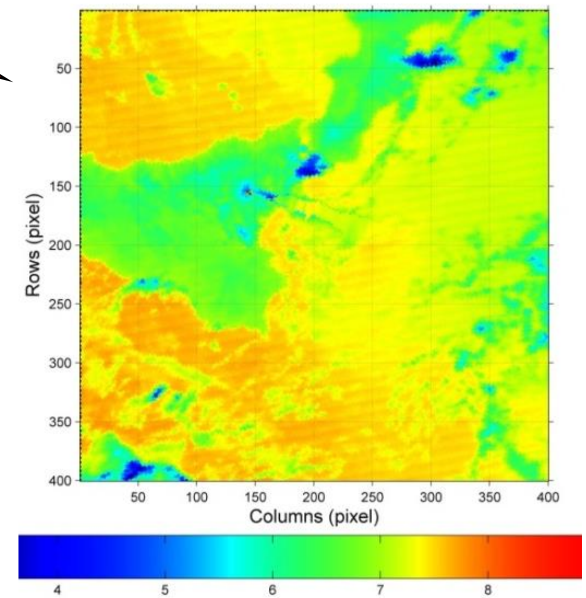
The volcanic cloud signal in the TIR spectral range can be seen as a region characterized by a dip in the radiance

Lp = original radiance with plume



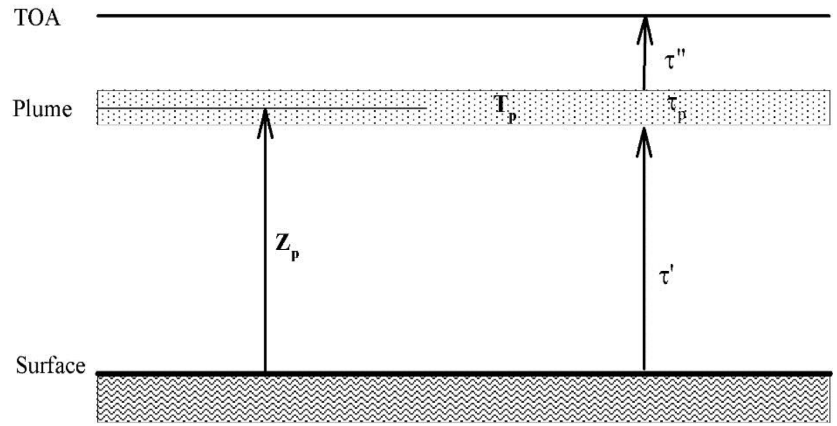
L0 = modified radiance without plume





Step 1) The VPR procedure starts with the removal of the plume from the image obtained by substituting the radiance values in the plume region with the interpolated values found in region surrounding the plume.

Step 2) The new image and the original data allow the computation of the **plume transmittance** (τ) in the TIR bands centred at 11 (τ'_{11}) and 12 (τ'_{12}) μm by **applying a simplified model** consisting of a plume with constant thickness, altitude and temperature



$$\tau'_p = \frac{L_p - (\tau_{p,SO_2})^{\mu} \cdot B(T)}{L_0 - B(T)}$$

→ **Function of Zp**

Step 3) The plume transmittances are then refined with a **polynomial relationship** obtained by means of MODTRAN simulations ***adapted for geographical region, ash type and atmospheric profiles***

$$\tau_p = \sum_{n=0}^{3} a_n \cdot (\tau'_p)^n$$

Step 4) By knowing τ_{11} and τ_{12} we can retrieve the ash **AOD** and the **Re** and then the **Ash mass** with the Wen and Rose (1994) simplified formula:

$$M = \frac{4}{3} S \rho \frac{R_e \, AOD_\lambda}{Q_{ext,\lambda}(R_e)}$$

Step 5) And finally, by exploiting the relationship between the τ_{11} and $\tau_{8.7}$ (only ash) we can compute $\tau_{8.7}$ of the **SO_2** only:

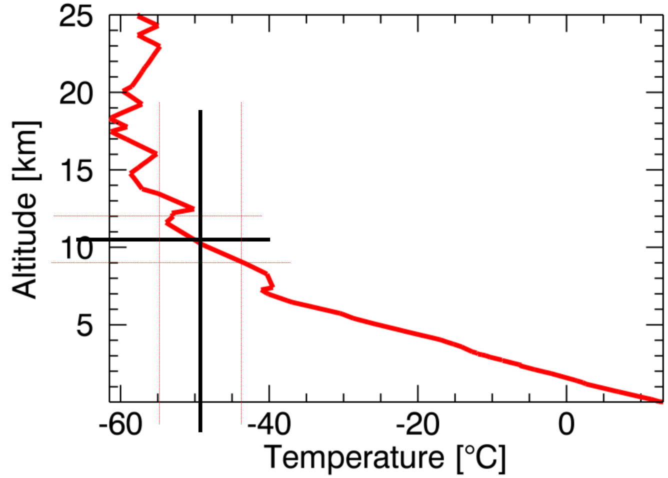
$$\tau_{p,SO2} = e^{-\mu \beta Cs}$$

Once the coefficients have been computed for a specific area, volcano and instrument, the only input is the **cloud altitude**

Volcanic cloud altitude computation

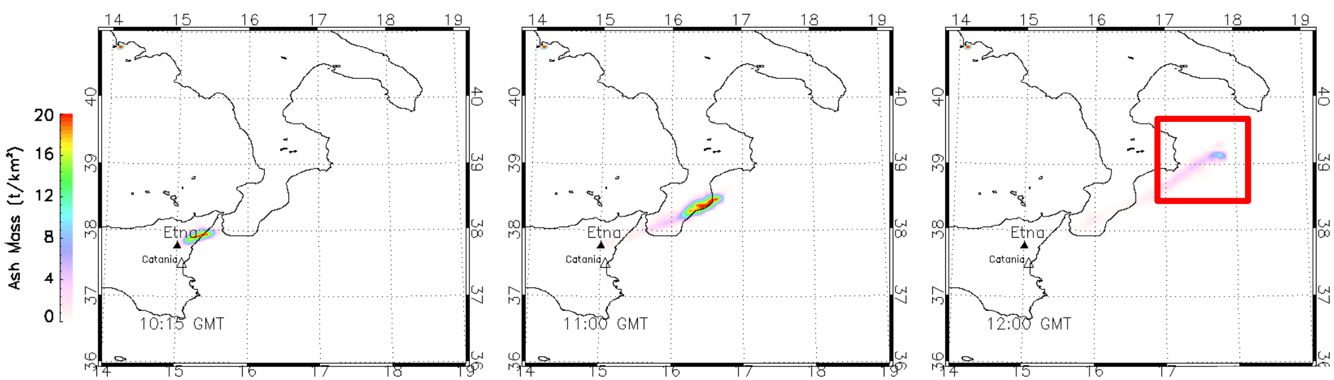
Dark pixels procedure:

The volcanic cloud altitude is obtained by comparing the Tb at 11μm of the satellite image 'dark pixels', with the atmospheric temperature profile of the nearest WMO meteo station of the area of interest *[Prata and Grant, 2001; Corradini et al., 2010; Scollo et al., 2014]*

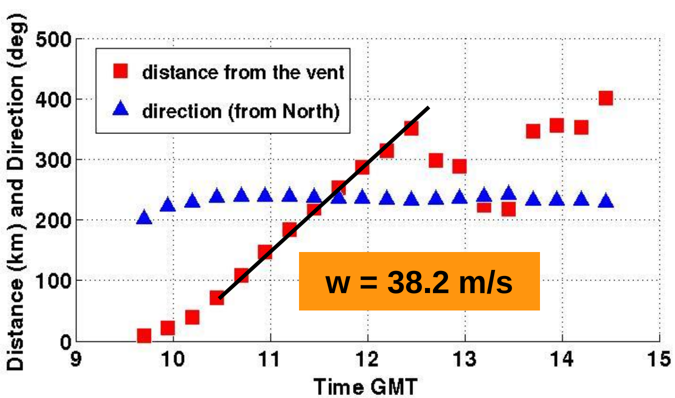


Tb(11μm) = - 49 +/- 5°C

Hp = 10.1 +/- 1.3 km

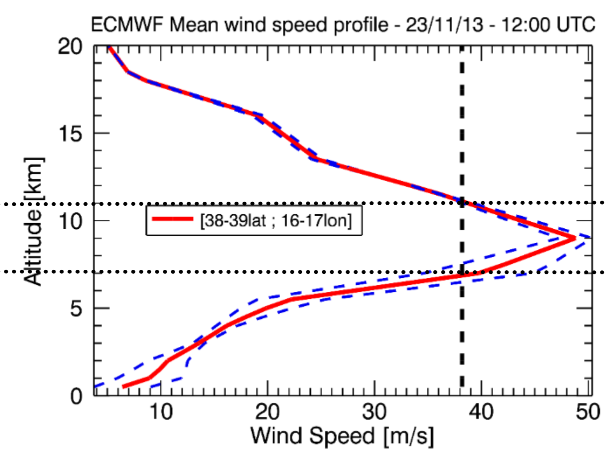


Track of the volcanic cloud center of mass:



Hp = 11 +/- 0.1 km

Hp = 7 +/- 0.5 km



Summary … and other techniques

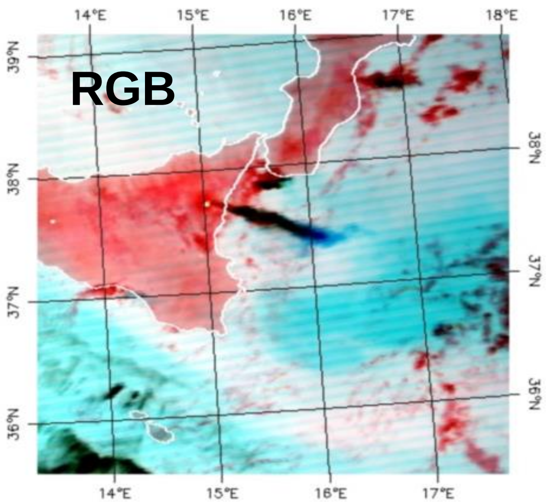
Procedure	Characteristics
Dark Pixels	➢ Very simple application ➢ Not applicable for diluted cloud ➢ *Tendency to underestimate the altitude*
Center of Mass	➢ Applicable only by using geostationary data
Cloud Shadow	➢ Applicable only during daytime ➢ Not applicable in case of diluted clouds
Satellite Parallax	➢ Critic in case of diluted clouds
CO_2 slicing	➢ For instruments with several channels inside the TIR CO_2 absorption band ➢ Critic in case of diluted clouds ➢ *Tendency to underestimate the altitude*

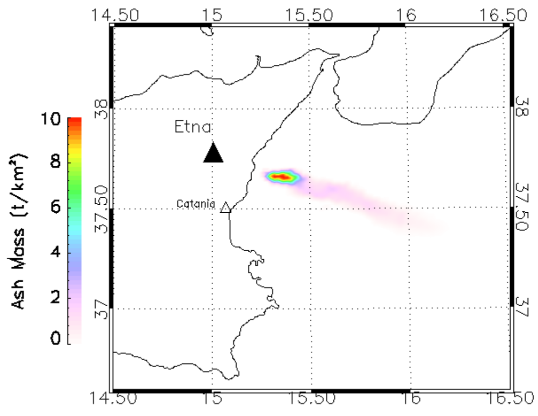
Test case event - October 23th 2011

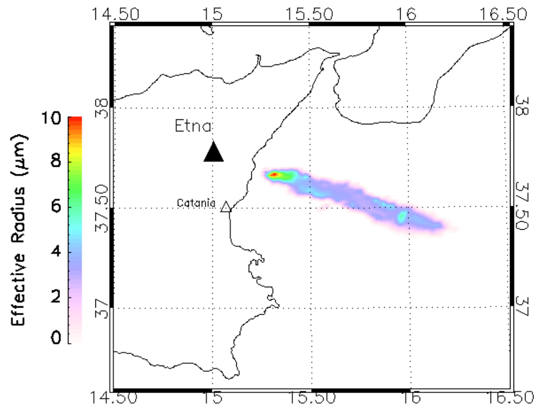
From *INGV-Catania report: “on the evening of 23 October 2011, the 17th paroxysmal eruptive episode occurred at the New Southeast Crater (New SEC) of Etna. The cloud of gas and tephra was carried eastward by the wind, leading to ash and lapilli falls in a sector from Zafferana Etnea and Milo to Giarre and Riposto from the 19:40 to 21:00”.*

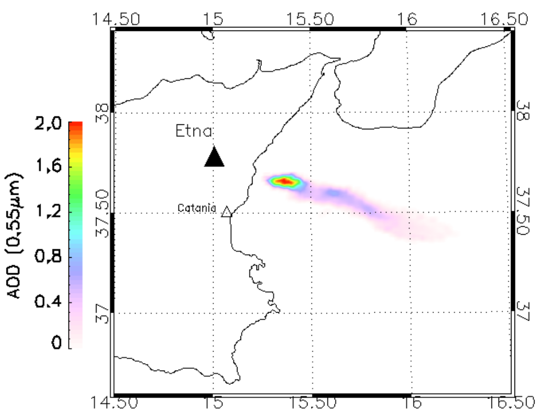
New south East crater, 20:40 GMT [*B. Bencke*]

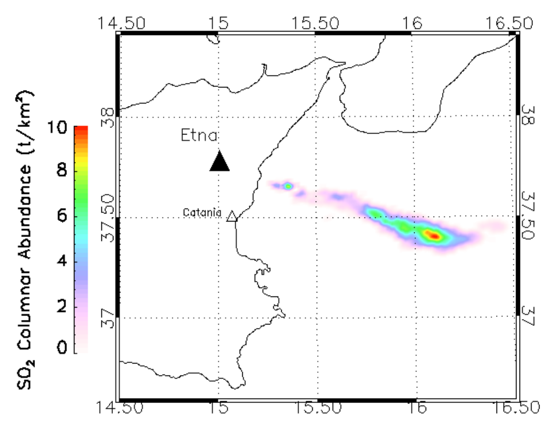
MODIS (21:30 UTC)







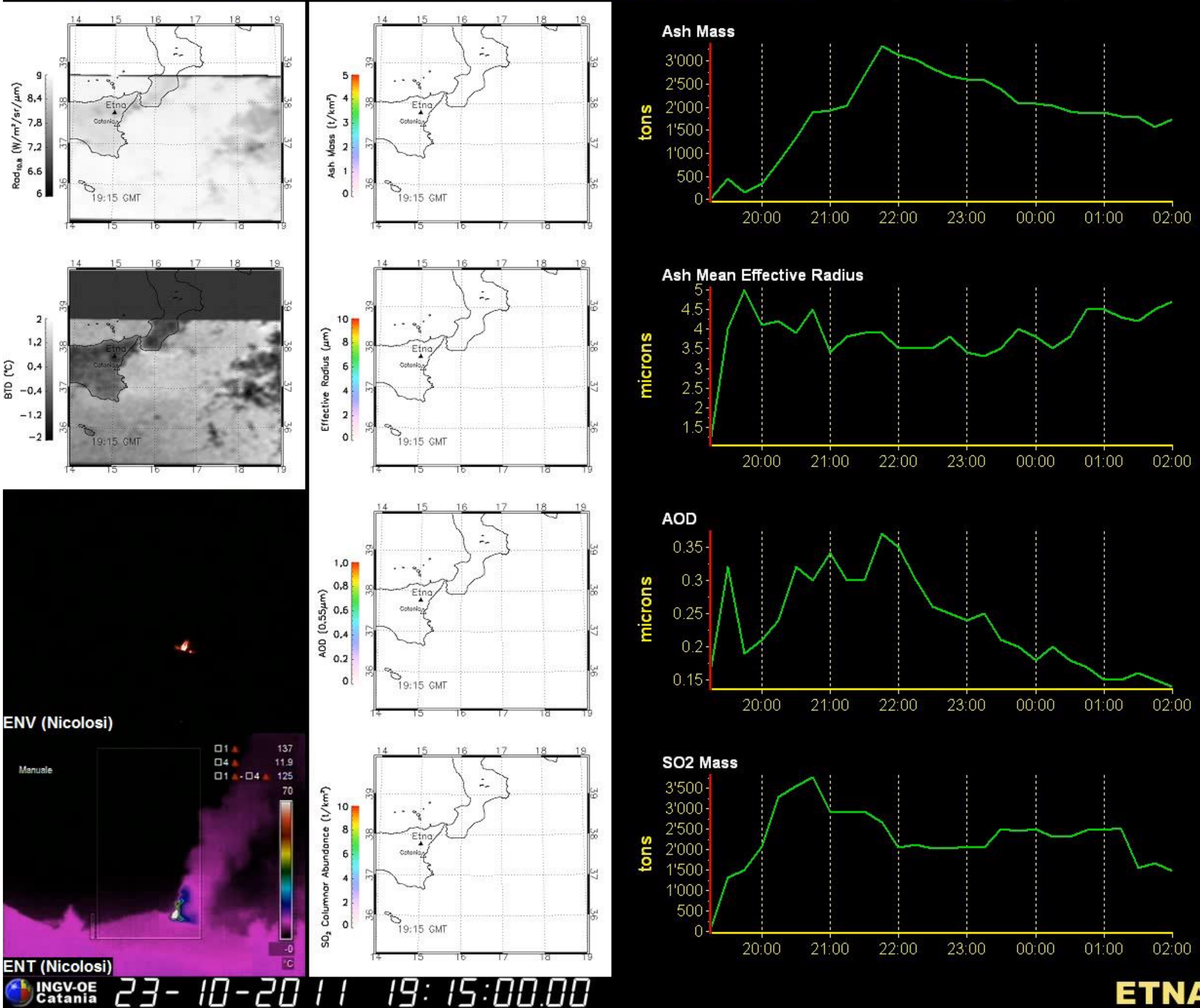




SEVIRI data

October 23th, 2011 ETNA LAVA FOUNTAIN

Ash/SO2 retrievals: Corradini S., Merucci L., Guerrieri L., Pugnaghi S.
Cameras: Pecora E., Biale E. **Editing:** Prestifilippo M.



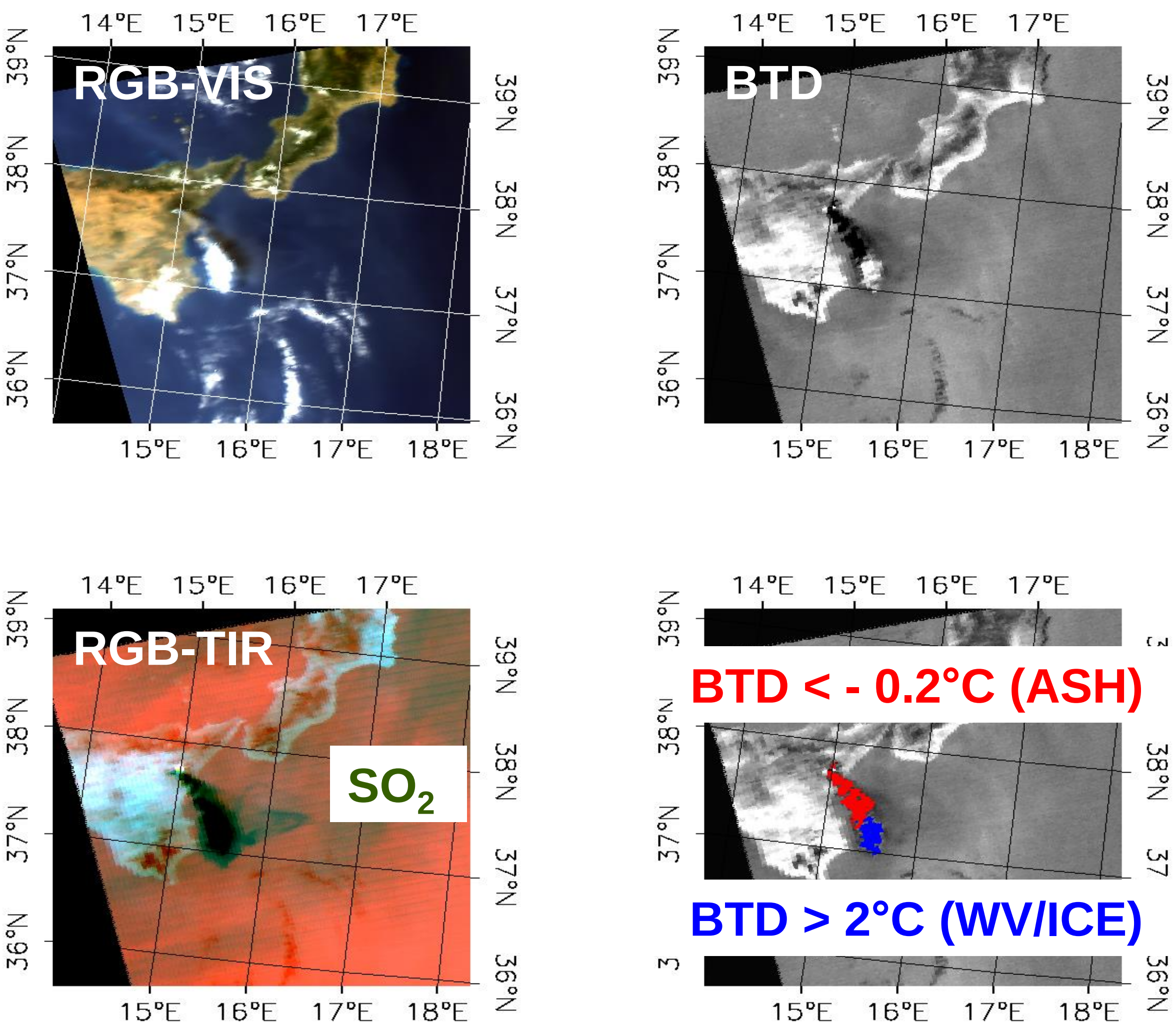
Overview

- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- **Volcanic Ice detection and retrievals**
- Sensitivity analysis
- Validation
- Conclusions

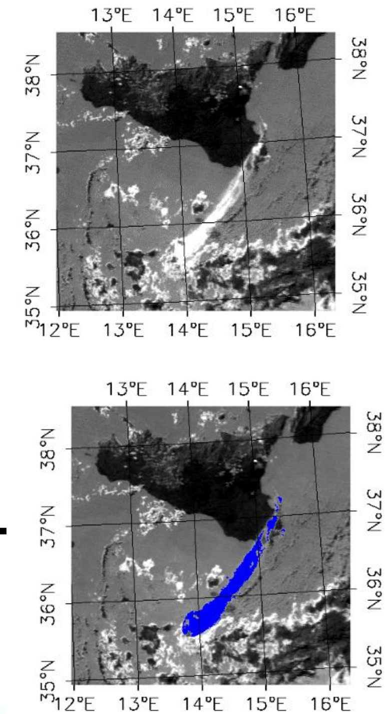
• **The Etna 2011 lava fountains produced volcanic clouds containing ash, gases and water vapour/ice particles**

• **In many cases the ash signal was completely hidden by the wv/ice particles**

Etna (Italy), 12 August 2011 MODIS-Aqua - 11:15 UTC

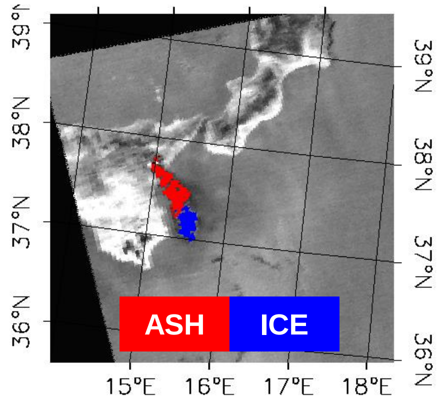


13 January 2011 MODIS-Aqua - 01:20 UTC



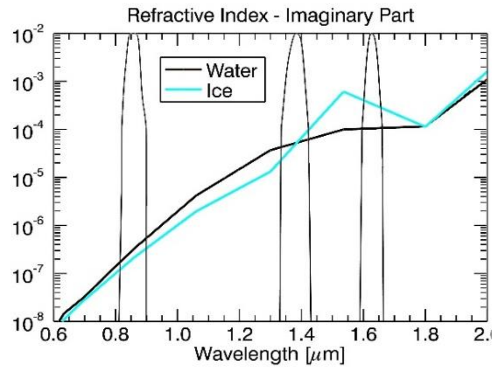
1) ASH *vs* WV/Ice discrimination
(using the BTD approach)

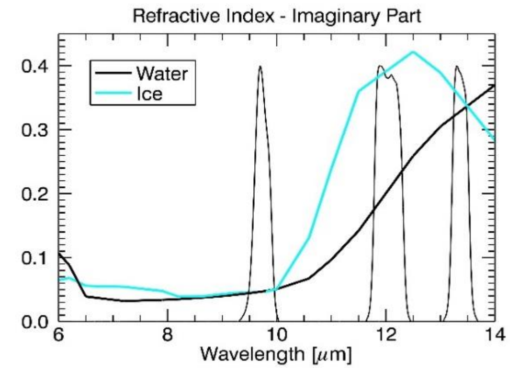
12 August 2011-11:15 UTC



WV/Ice detection and retrieval

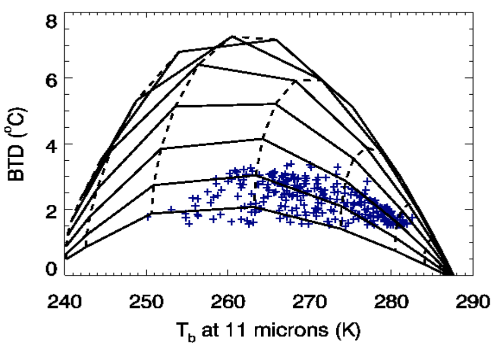
2) WV *vs* Ice discrimination
(using the VIS-SWIR channels during daytime)





3) WV/Ice retrievals

LUT:
computing the "BTD-Tb(11μm)" curves using the WV/Ice optical properties

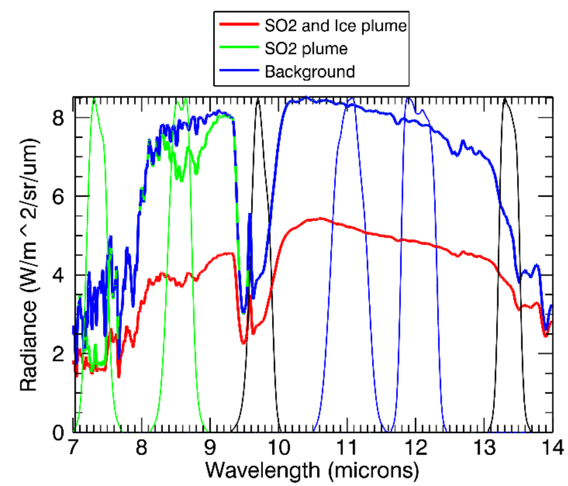


VPR:
computing the coefficients by considering the WV/Ice optical properties

WV/Ice effect on SO_2 retrieval

- As the plume ash particles, the WV/Ice particles reduce the top of atmosphere radiance in the entire TIR spectral range, including the channels used for the SO_2 retrieval

- The net effect is a significant SO_2 overestimation



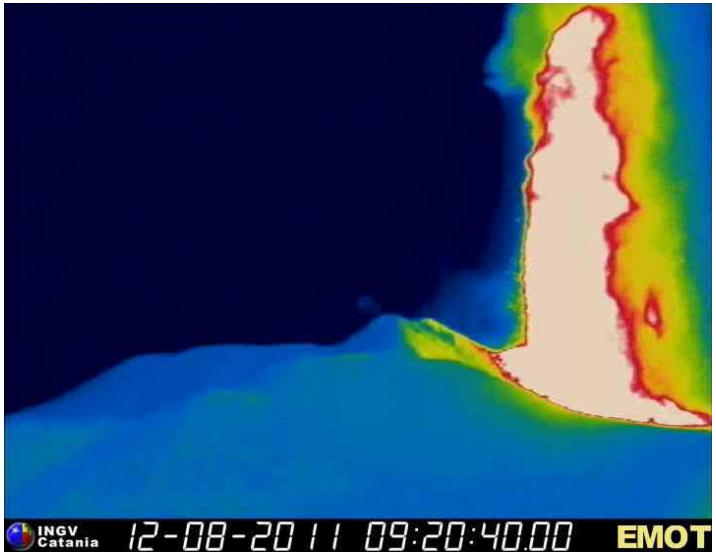
LUT:

$$\chi^2_{c_s}(n,m) = \sum_{i=1}^{n} \left[\frac{L^S_{(n,m),i} - L^M_{(n,m),i}(c_{s,j}, AOD^{ice}_{(n,m)}, R^{ice}_{e,(n,m)})}{L^S_{(n,m),i}} \right]^2 w_i$$

Test case event - August 12th 2011

From INGV-Catania reports [B. Bencke]: the lava fountain started at 8:30 UTC reaching an height of several hundred meters with ash and lapilli fall that reached the village of Zafferana Etnea. A plume of mixed ash and SO_2 was emitted at an altitude of about 7 km. The explosive activity decreased after 10:30 and from 11:00 faded with weak ash pulses lasted half an hour.

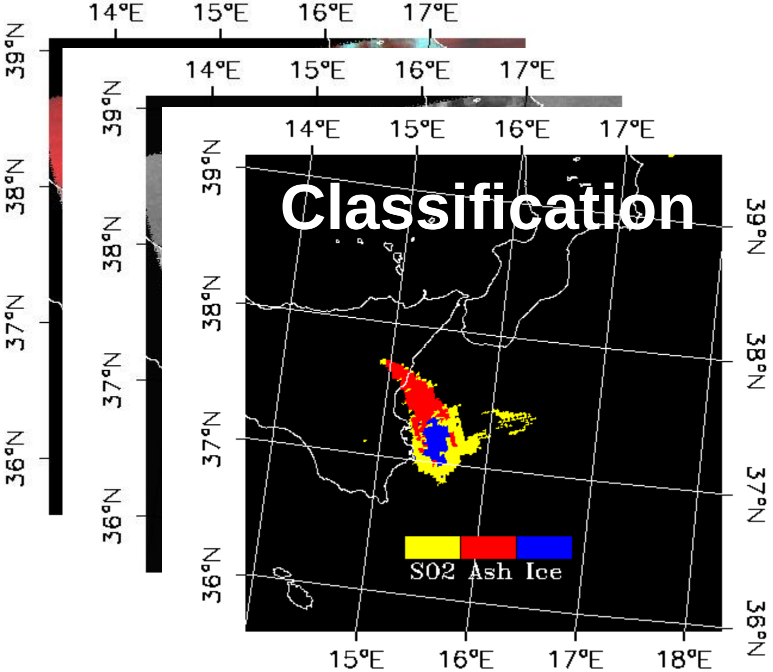
The satellite images emphasized the simultaneous presence of ash, SO_2 and Ice in the volcanic cloud.



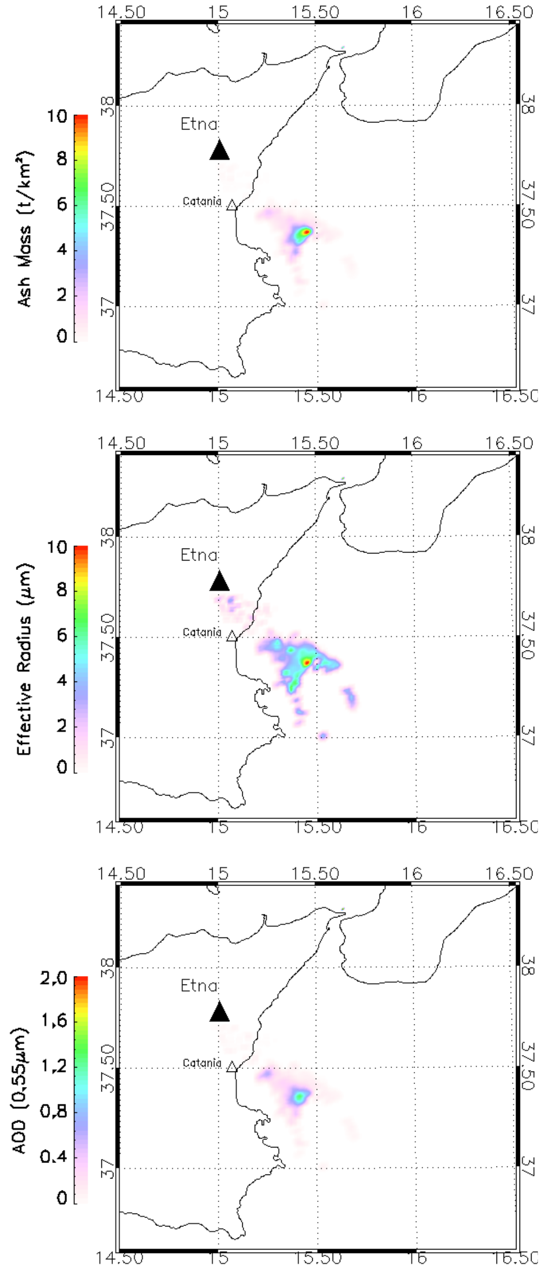
IR camera located on la Montagnola

Courtesy from Elisabetta Ferrera, University of Catania

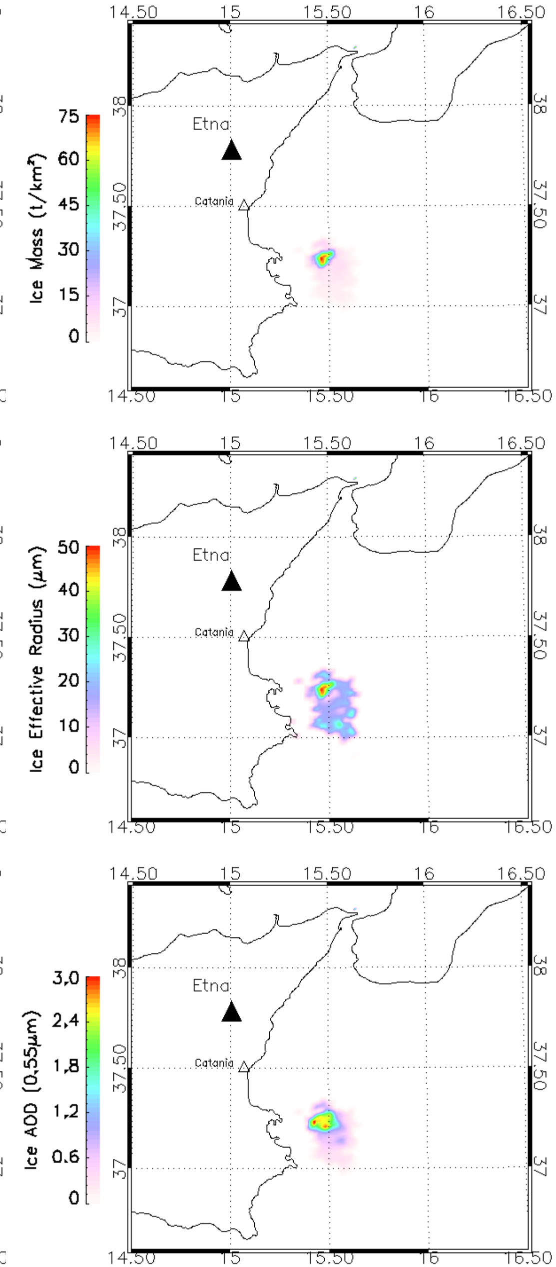
MODIS data (11:15 UTC)



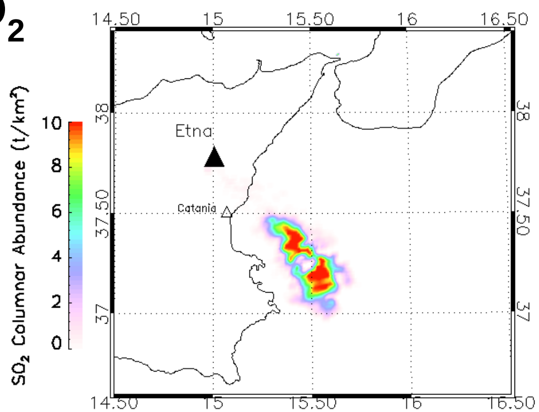
Ash



Ice



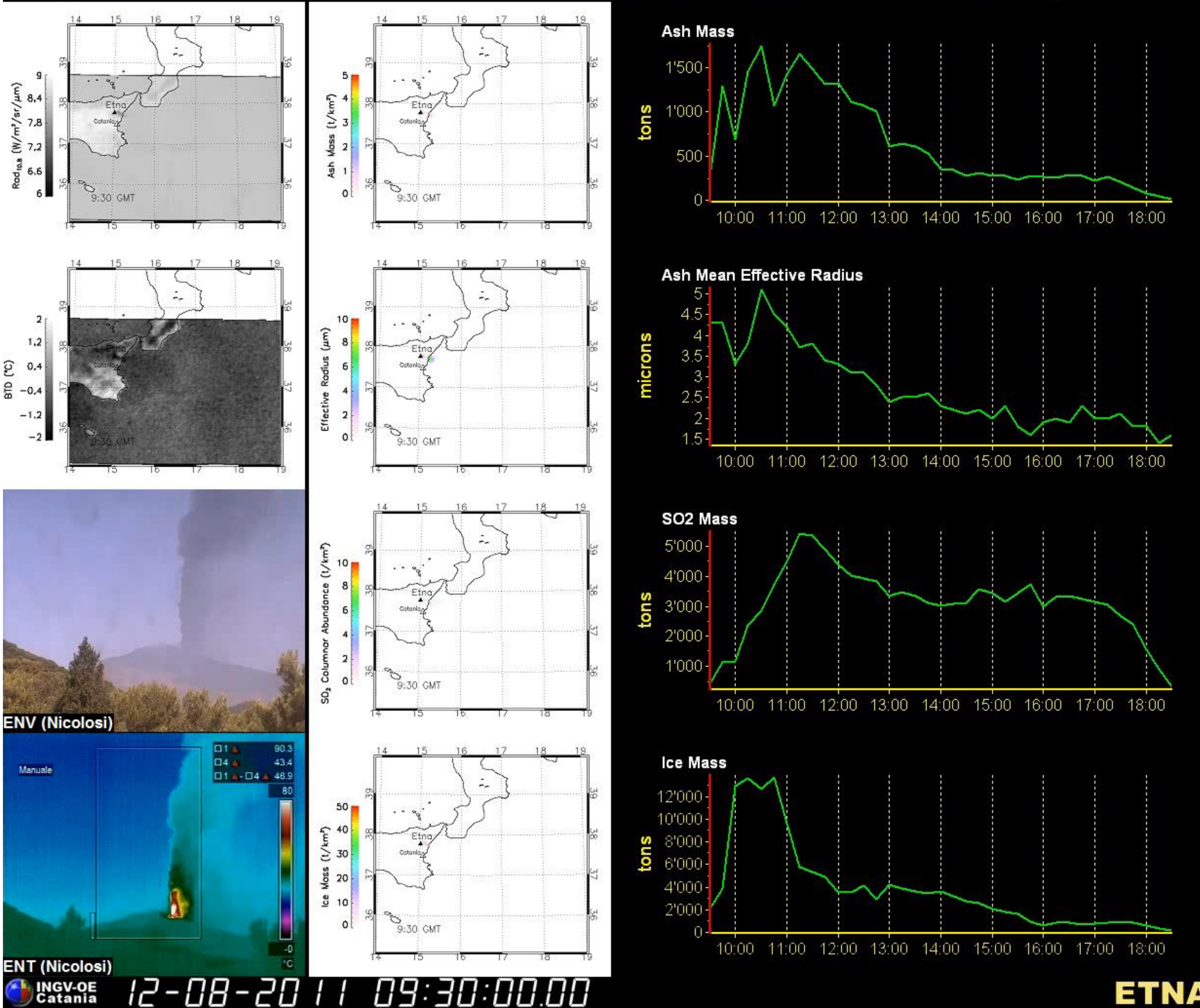
SO_2



SEVIRI data

August 12th, 2011 ETNA LAVA FOUNTAIN

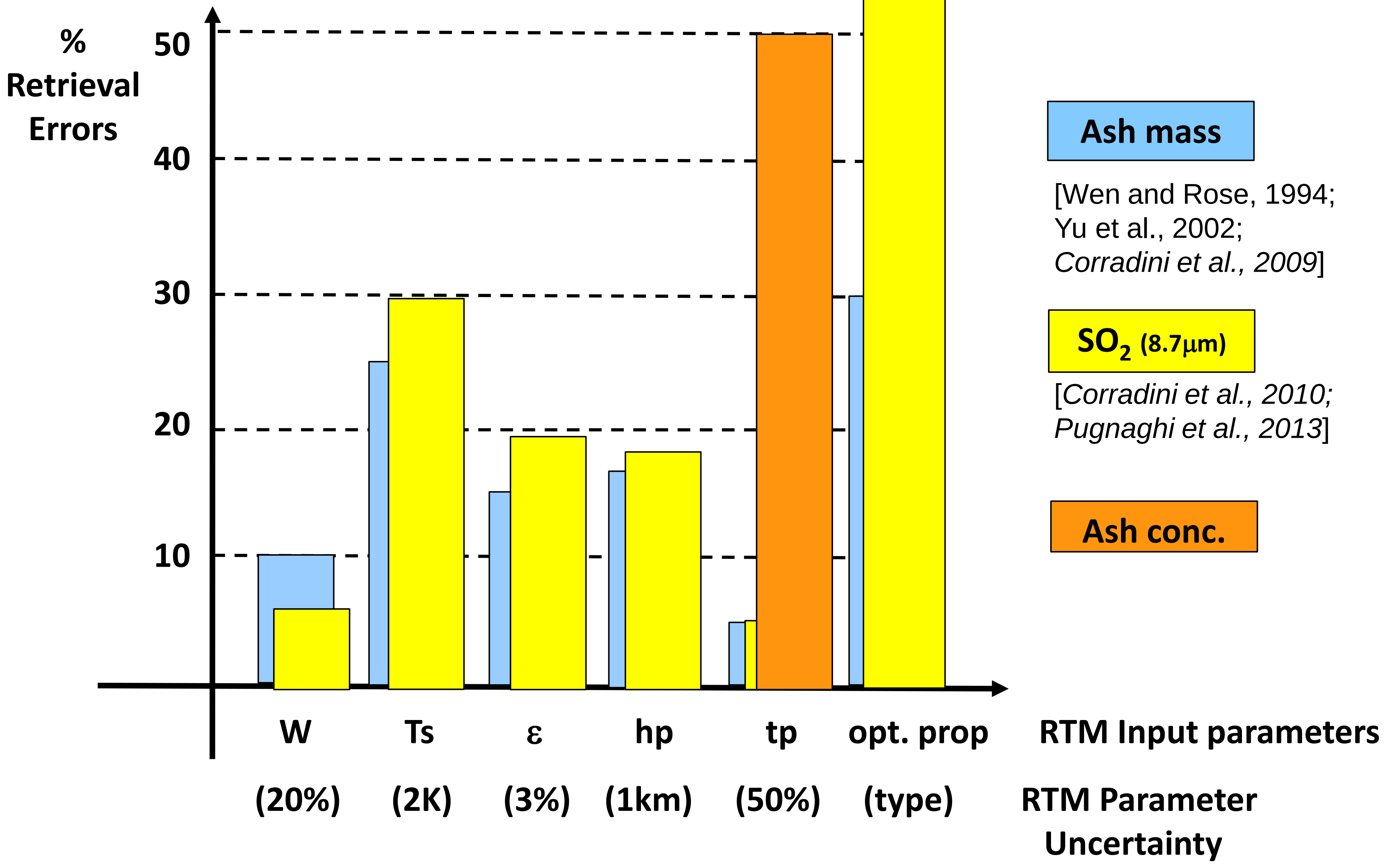
Ash/SO2/Ice retrievals: Corradini S., Merucci L., Guerrieri L., Pugnaghi S.
Cameras: Pecora E., Biale E. **Editing:** Prestifilippo M.



Overview

- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- **Sensitivity analysis**
- Validation
- Conclusions

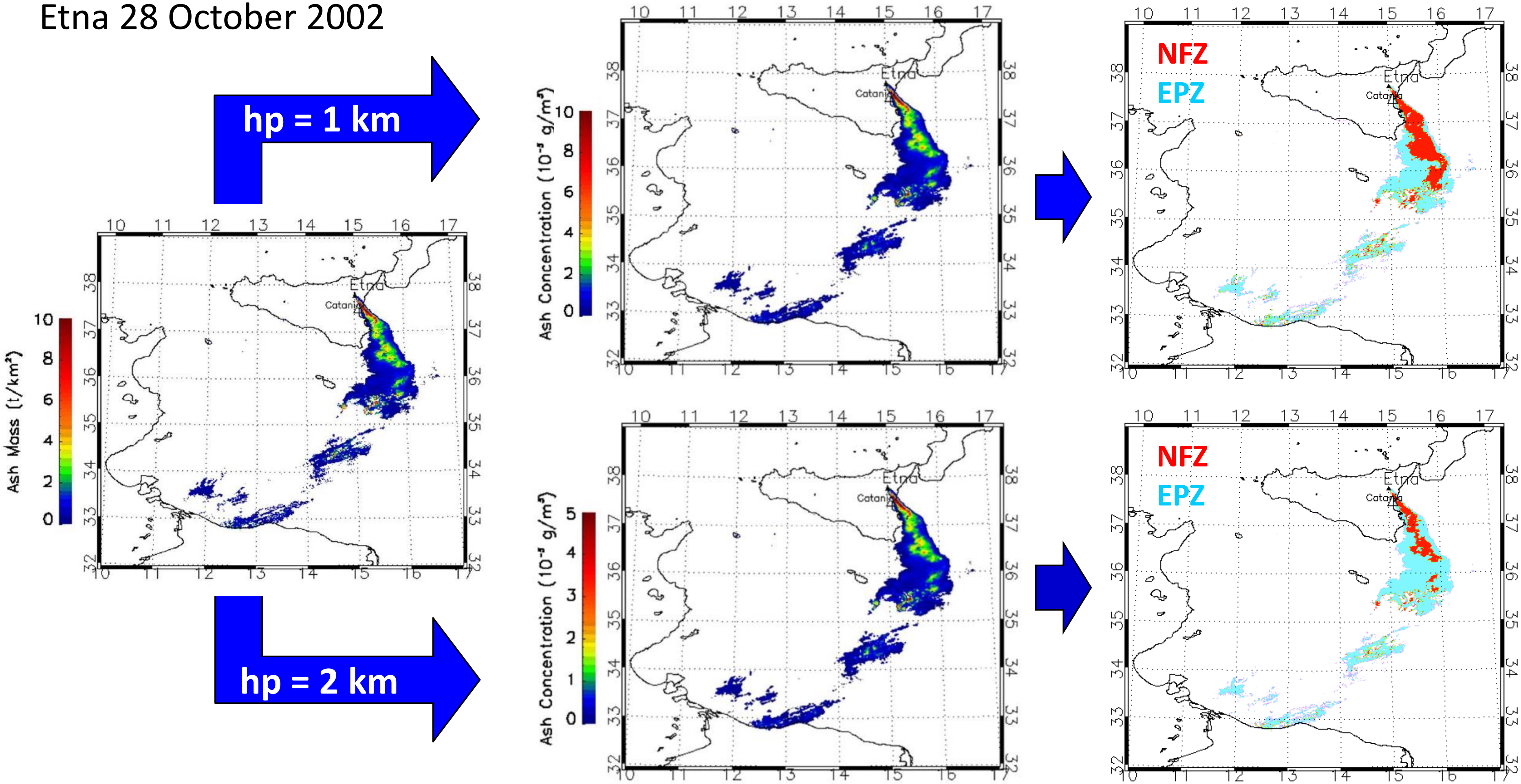
Each RTM input parameter has an uncertainty that lead to ash and SO_2 retrieval errors



MODIS-Aqua,

Etna 28 October 2002

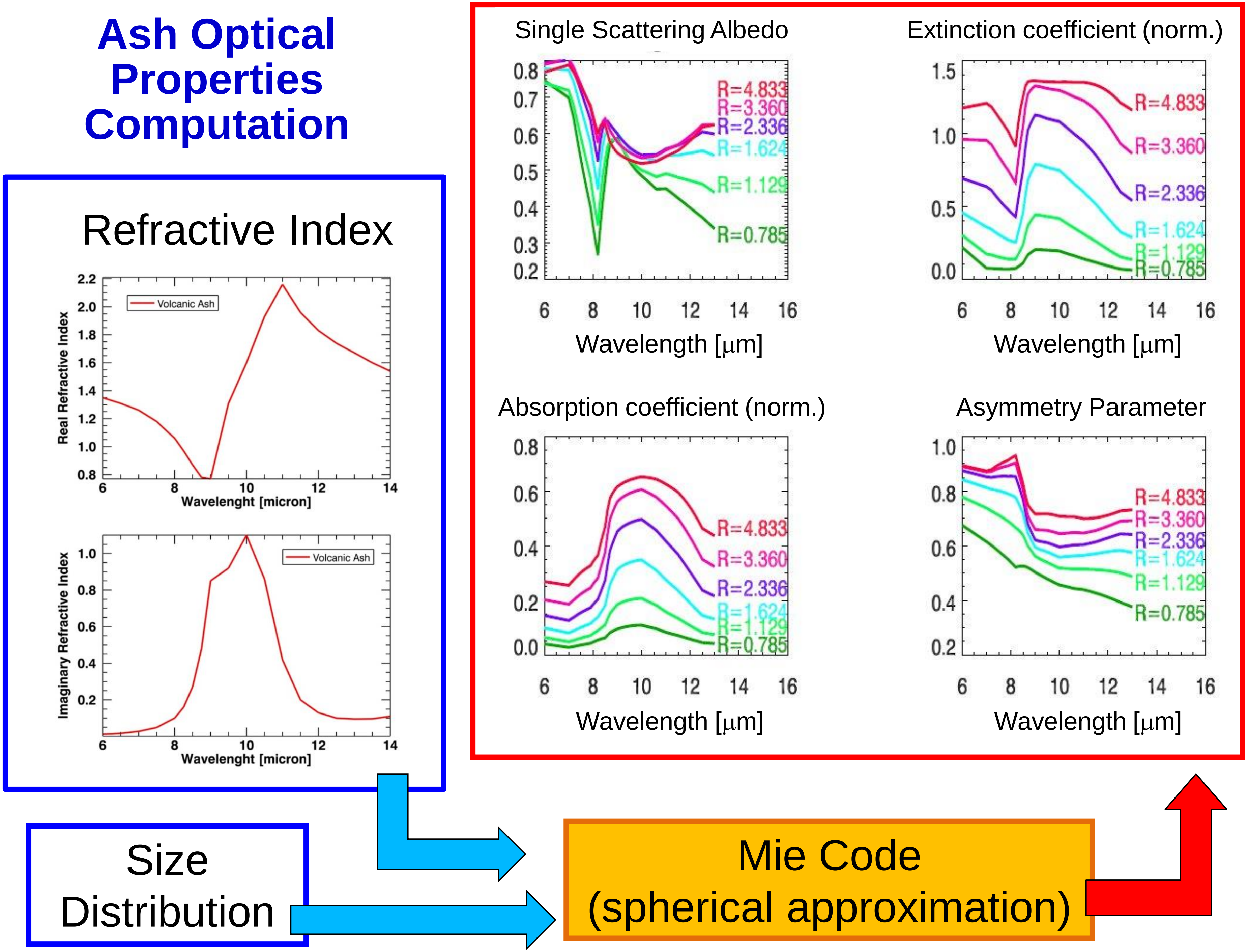
Ash cloud thickness



- ***No Fly Zone (NFZ)***: Any area where volcanic ash concentrations are predicted to be higher than 2 x 10^{-3} gm^{-3}

- ***Enhanced Procedures Zone (EPZ)***: Any area where volcanic ash concentrations are predicted to be between 2 x 10^{-4} gm^{-3} and 2 x 10^{-3} gm^{-3}.

Ash Optical Properties Computation

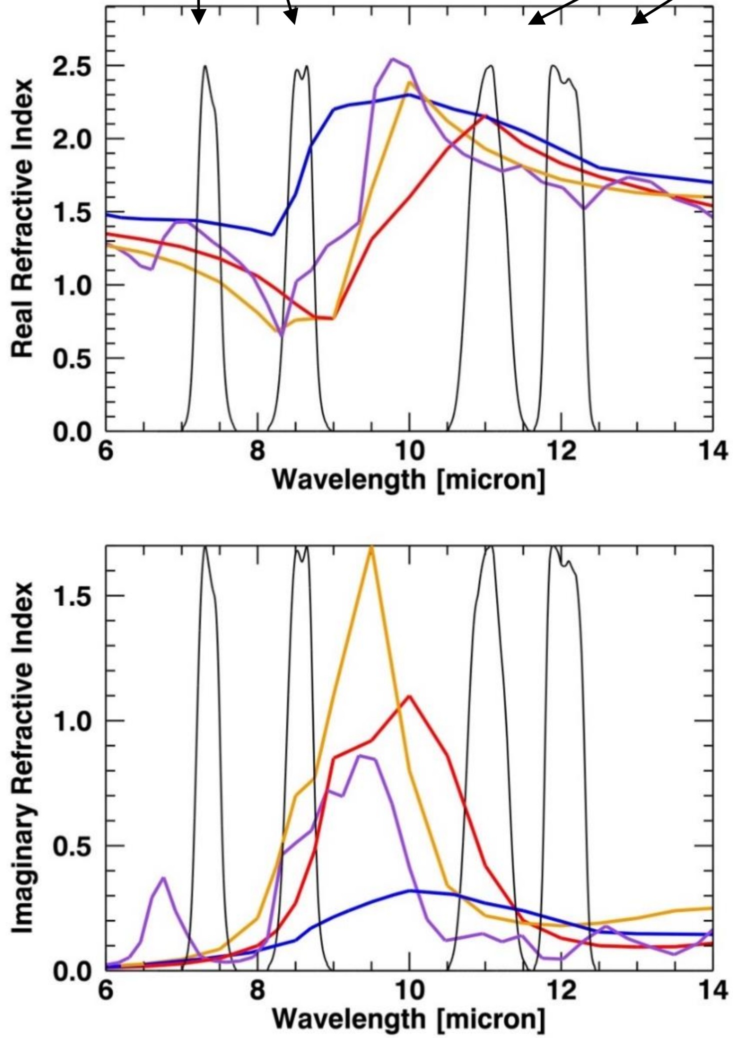


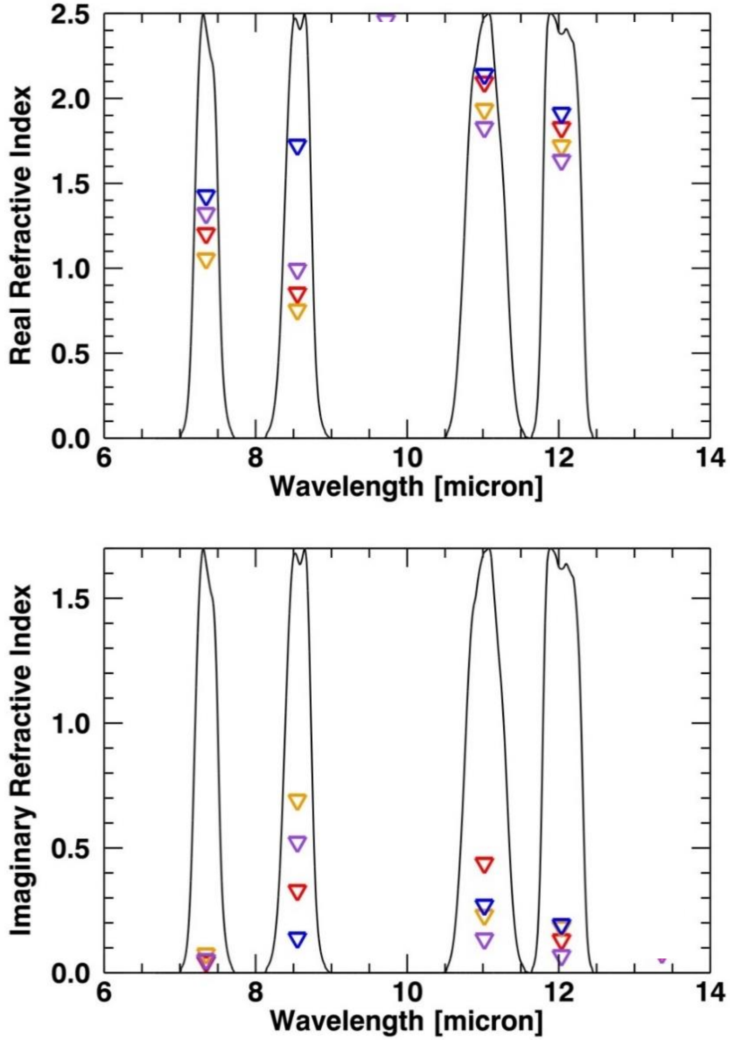
Ash refractive index

ARIA Database

http://www.atm.ox.ac.uk/project/RI/introduction.html

SO_2 retrieval (7.3, 8.6 μm) **Ash retrieval (11, 12 μm)**



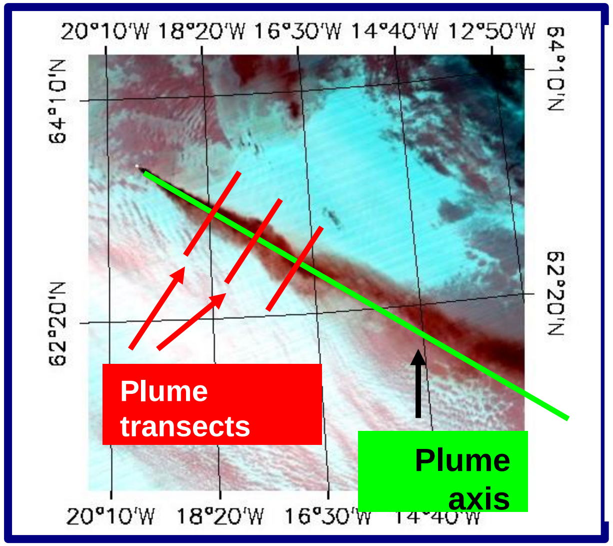


MODIS data collected on Eyja 2010 eruption

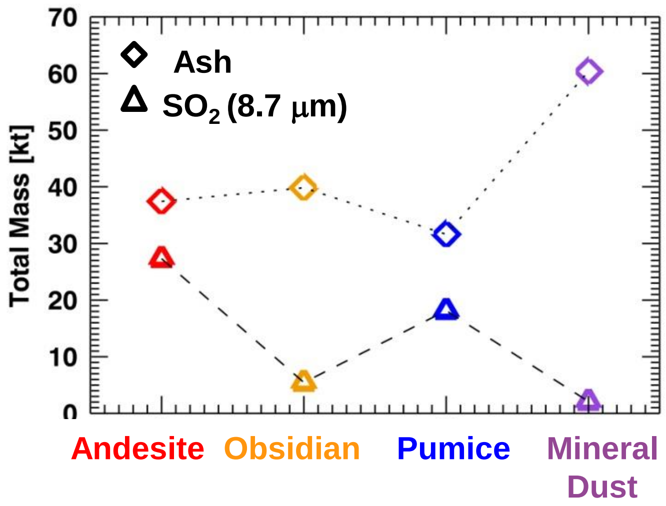
The 4 selected refractive indexes have been used to process the MODIS images collected the May 12, 2010 at 22:35 UTC

$$F_t = w_s\, l_{(n,m)} \sum_t m_{(n,m)}$$

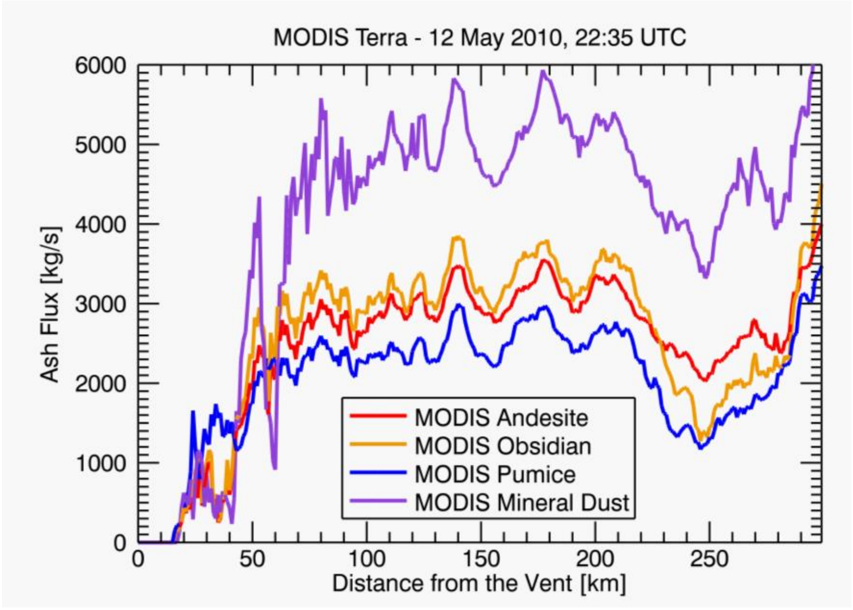
$$\forall (n,m) \in t$$



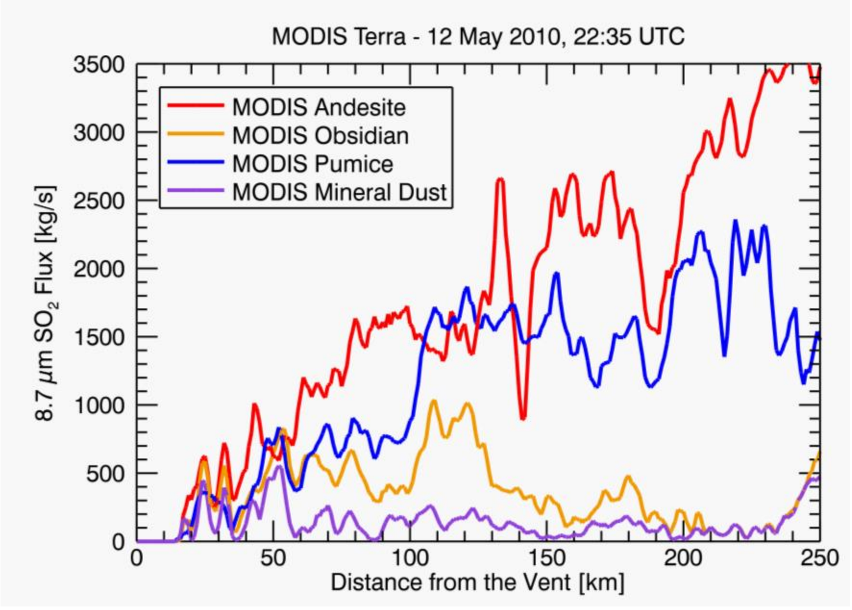
Total Mass



Ash Flux



SO_2 8.7 μm Flux



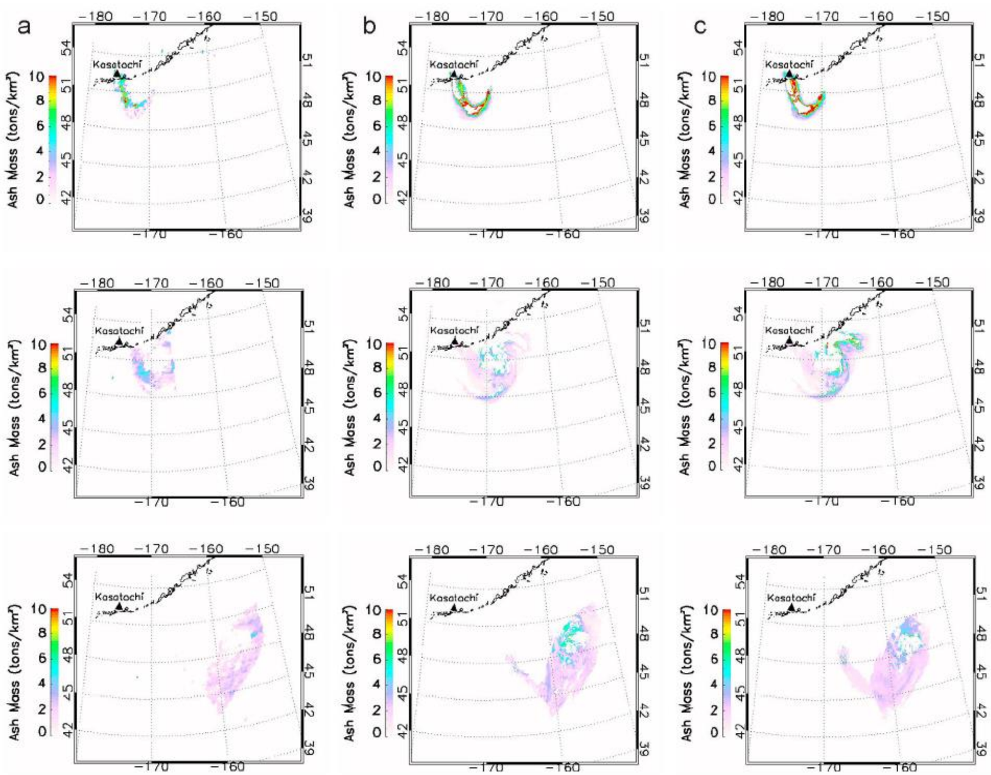
Overview

- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- **Validation**
- Conclusions

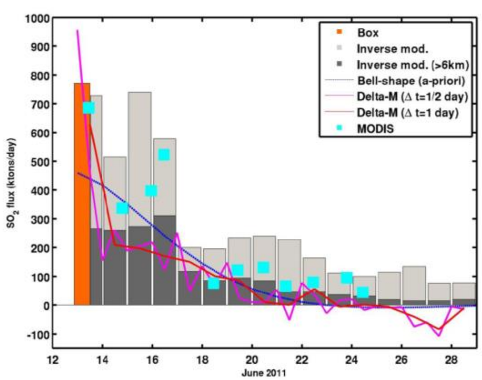
Cross-Comparison and Validation

Satellite cross-comparison

AIRS **MODIS** **AVHRR**



Kasatochi 2008 Eruption *[Corradini et al., JGR, 2010]*

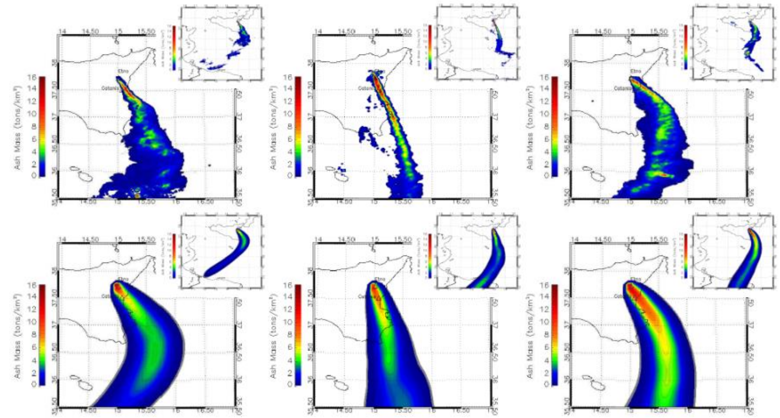


Satellite SO_2 flux cross-comparison

OMI, IASI, GOME2, MODIS, Nabro 2011 Eruption

[Theys et al., ACP, 2013]

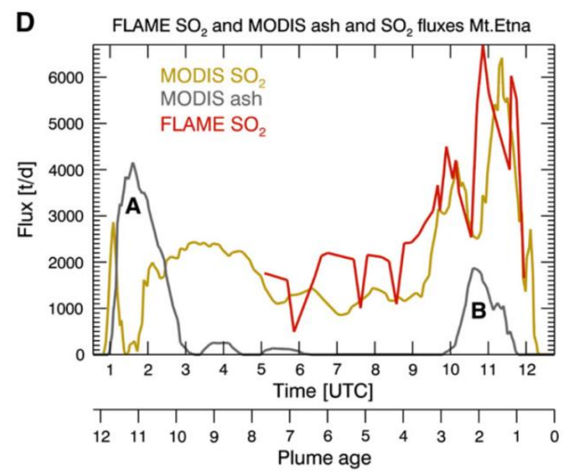
Satellite-Models



MODIS vs FALL3D Etna 2002 Eruption

[Corradini et al., IEEE, 2011]

Satellite - ground systems



MODIS vs FLAME, Etna 2006 Eruption

[Merucci et al., JVGR, 2011]

Overview

- Introduction
- MODIS and SEVIRI multispectral satellite sensors
- Ash and SO_2 detection
- Ash and SO_2 retrievals
  - LUT approach
  - VPR approach
- Volcanic Ice detection and retrievals
- Sensitivity analysis
- Validation
- **Conclusions**

✓ The use of the multispectral satellite sensors data collected from MODIS and SEVIRI have been proven to be efficient and the retrieval techniques effective

However, some criticalities still occur …

Ash Optical Properties →

- **Laboratory measurements**
- **Use of multispectral systems to characterize the spectra**

Volcanic cloud thickness →

- **Lidar satellite and ground systems (lidar, radar, VIS-TIR cameras)**

Volcanic ice/wv →

- **Improve the ice/wv discrimination**

✓ As one system cannot give a comprehensive description of the eruptive activity, exploit the capabilities to use different systems by integrating their measurements

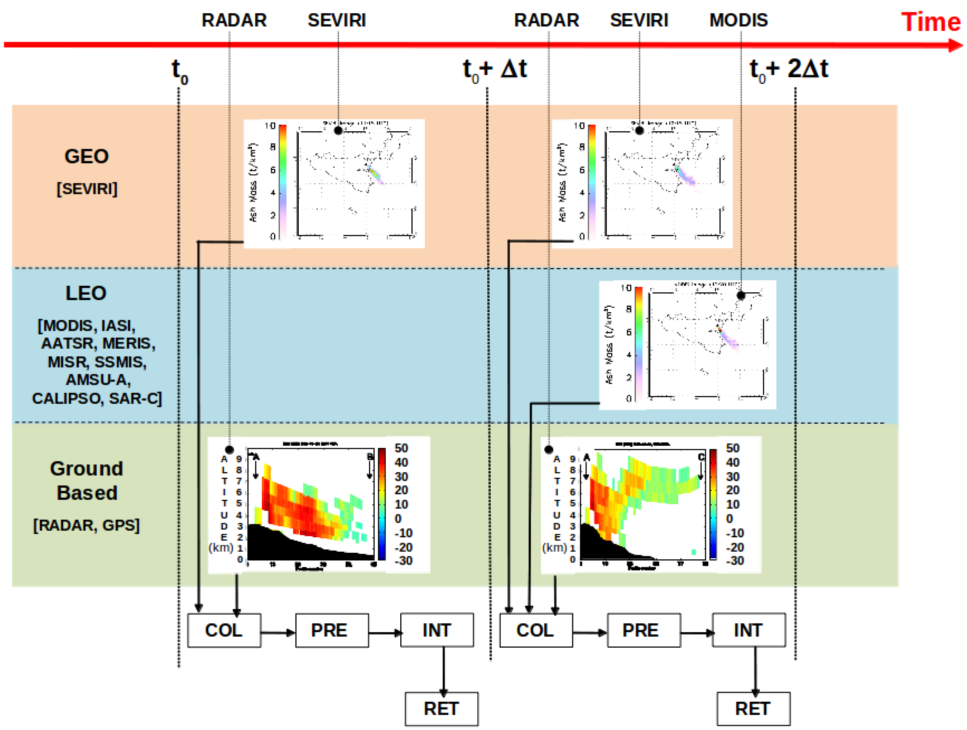
The APhoRISM FP7-EU Project

APhoRISM is a 3 years FP7-EU project started on December, 2013 that aims to ***develop innovative products*** to support the management and mitigation of the **volcanic** and the **seismic** crisis. Satellite and ground measurements will be managed in a novel manner to ***provide new and improved products in terms of accuracy and quality of information***.

APHORISM
ADVANCED PROCEDURES FOR VOLCANIC AND SEISMIC MONITORING

www.aphorism-project.eu/

The ***Multi-platform volcanic Ash Cloud Estimation (MACE)*** procedure will exploit the complementarity between geostationary, and polar satellite sensors and ground based measurements.
Mace is based on GEO-SEVIRI measurements. The basic idea is to continuously ***improve*** both ***the SEVIRI ash retrievals*** and the ***source characterization*** by integrating all the LEO and ground-based information from VIS to MW in clear and cloudy sky conditions.



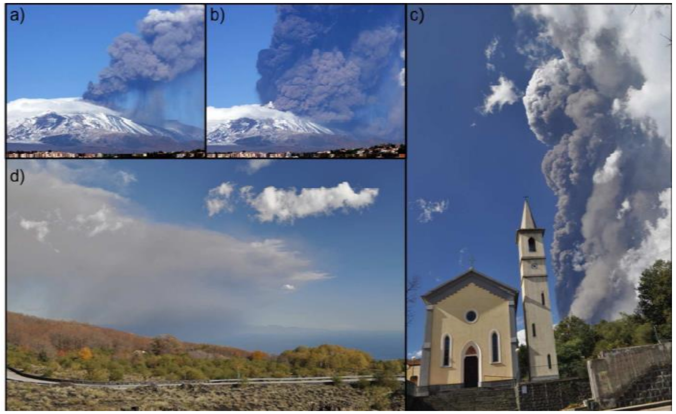
MACE temporal flow diagram

Test Cases

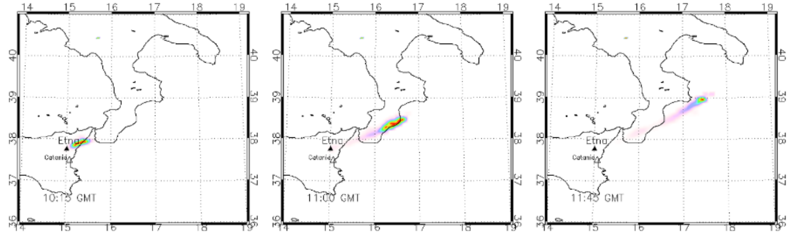
MACE ash products will be tested on 3 recent eruptions representative of different eruption styles in different clear or cloudy atmospheric conditions: Eyjafjallajokull (Iceland) 2010, Grimsvotn (Iceland) 2011 and Etna (Italy) 2011-2014.

23 November 2013 Etna lava fountain

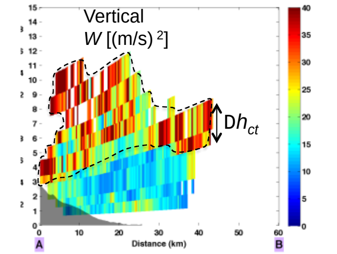
This episode has been detected from:

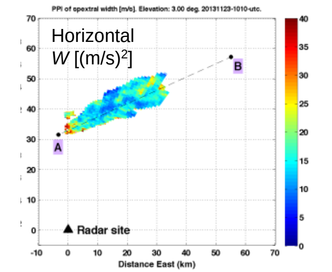


GEO-SEVIRI

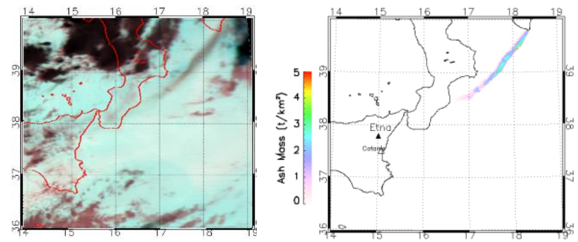


Ground-RADAR X

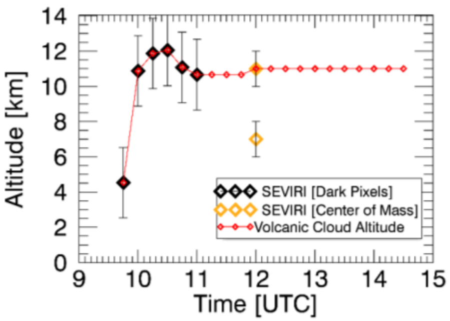


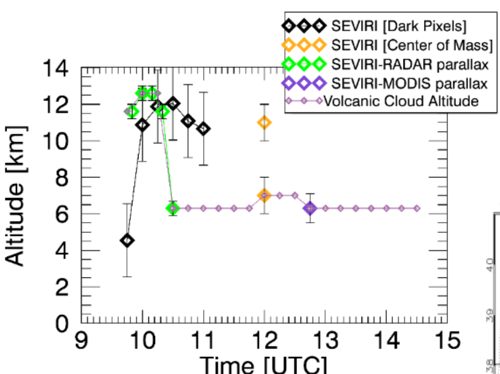


LEO-MODIS

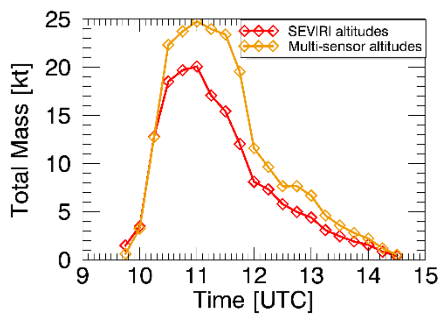


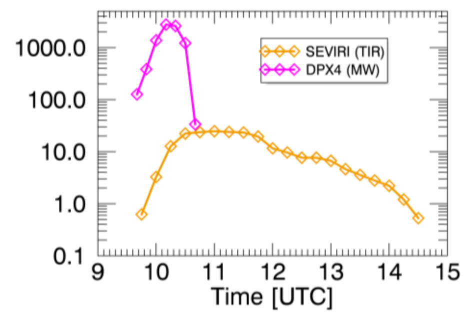
Volcanic cloud layers



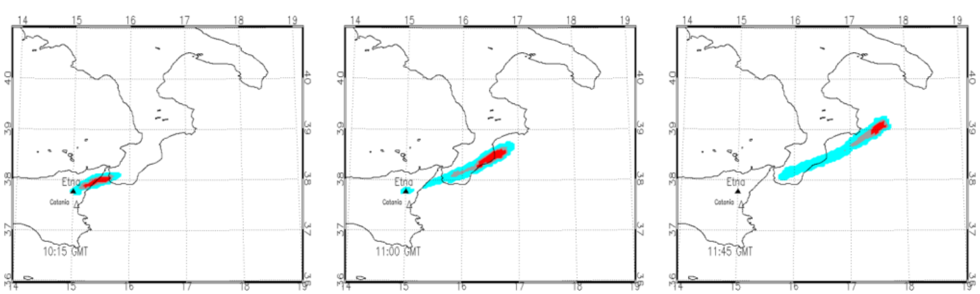


Volcanic Ash Mass

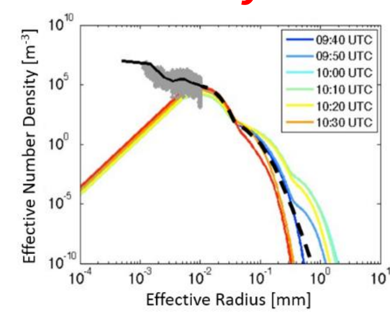




Volcanic Ash Concentration Classification



Effective Number Density



[Corradini et al., 2016]

THANKS FOR YOUR ATTENTION

Credit: *Francesco Ciancitto , INGV-OE*

Etna eruption, 26/10/2013