The impact of Aeolus on Volcanic Ash quantitative dispersion modeling by applying inversion techniques on volcanic emissions

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Introduction

- Volcanic ash dispersion forecasting is vital for aviation and the accuracy is depended on both to the **wind fields** and the knowledge of the **source term** of the eruption.
- Aeolus wind data assimilation by ECMWF provides improved meteorological fields for advection calculations in volcanic ash dispersion models.
- In the framework of the **NEWTON ESA study,** we examined the potential improvements on **Etna** volcanic plume forecasts due to Aeolus assimilated meteorological fields (**published at Scientific Reports**).
- We initiate the **Early Warning System (EWS)** developed within the **e-shape EuroGEO project** in support of the Volcanic Ash Advisory Centers (VAACs).

Early Warning System at the PANGEA-NOA during e-shape – EuroGEO project

(1) VOLCANO OBSERVATORY NOTICE FOR AVIATION (VONA)	
(2) Issued:	20210312/0844Z
(3) Volcano:	Etna 211060
(4) Current Color Code:	**RED**
(5) Previous Color Code:	red
(6) Source:	Etna Volcano Observatory
(7) Notice Number:	2021/0047/06C10
(8) Volcano Location:	3744N 01500E
(9) Area:	Italy
(10) Summit Elevation:	3300 m
(11) Volcanic Activity Summary:	STRONG ASH EMISSION ONGOING
(12) Volcanic cloud height:	ESTIMATED VOLCANIC CLOUD HEIGHT IS 9000 M AT THE TOP; DATA FROM SATELLITE, SURVEILLANCE CAMERA AND PERSONAL ON FIELD
(13) Other volcanic cloud information:	ASH FALLOUT IS REPORTED ON FLERI LOCALITY AT 550 M ASL ON E VOLCANO FLANK
(14) Remarks:	THE PHENOMENON IS OBSERVED BY SATELLITE, SURVEILLANCE CAMERA AND INGV PERSONAL ON FIELD

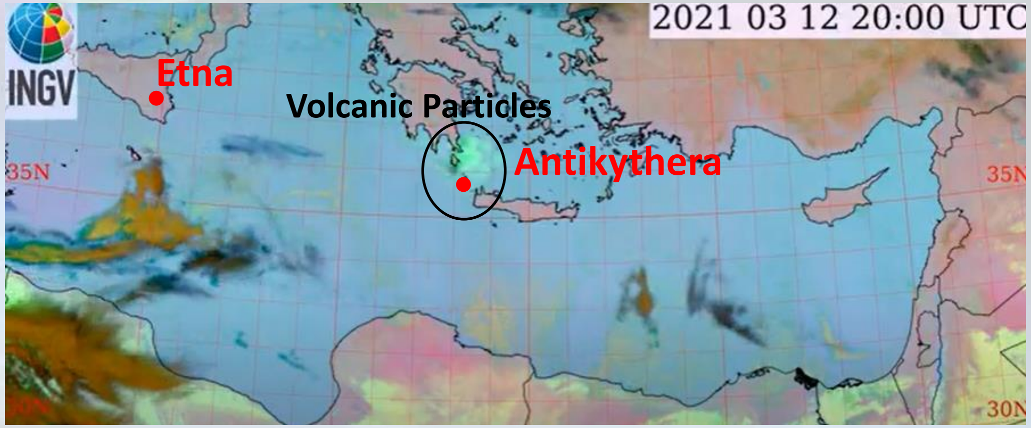
TIME

PLUME HEIGHT

(more information about EWS Kampouri et al., 2021)

VONA ALERTS

MSG-SEVIRI



- Near-real-time **alerts** from Etna volcano eruptions.
- The alerts are used in the PANGEA to **forecast** the volcanic plume pathway and **identify** the volcanic particles above the area the days following an eruption.
- Lidar observations are used for model evaluation and improvement.

VONA messages of INGV-EO → PANGEA-NOA Polly^{XT} lidar → FLEXPART-WRF

→ **Sulfates Simulations**

→ **Ash Simulations**

(https://react.space.noa.gr/intranet/volcano-ews)

EuroGEO INGV e-shape esa

Workflow

Initial and boundary conditions

IFS outputs [ECMWF]

Exp1:

Control without assimilating Aeolus

Exp2:

Assimilated Aeolus Rayleigh-clear and Mie cloudy HLOS wind fields

Angela Benedetti
Michael Rennie

WRF-ARW regional atmospheric model

Initialization of WRF-NOA

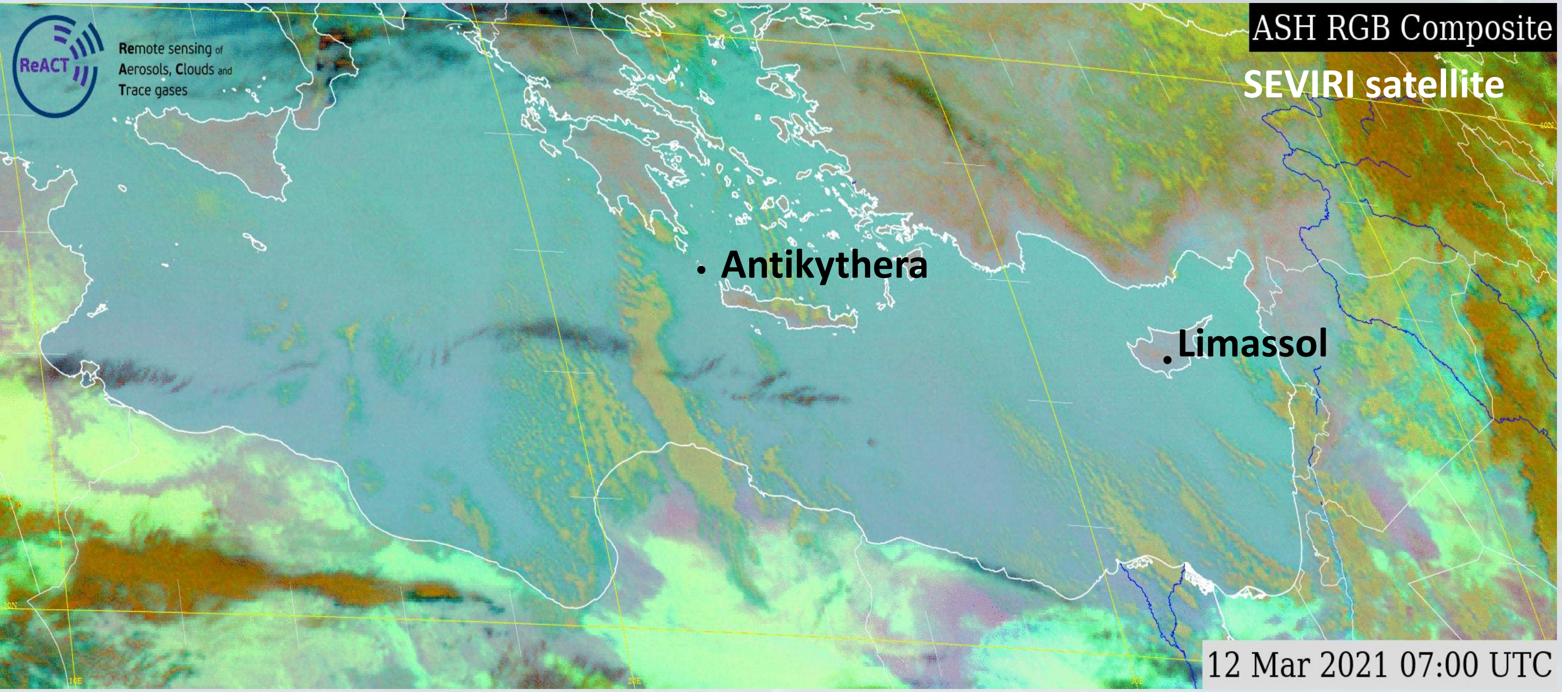
48 hours WRF forecast runs initialized with 2 sets of IFS outputs (**with/w-o Aeolus**) at 12 March 2021, 00:00 UTC (boundary conditions every 6 hours)

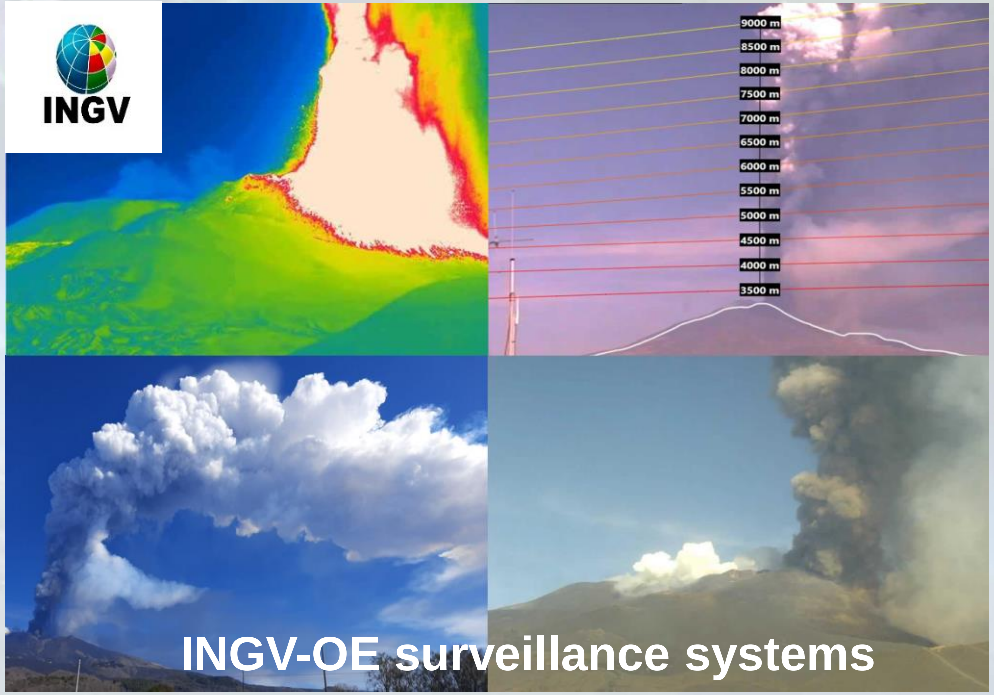
FLEXPART-WRF dispersion model

WRF meteorological fields **drive** **FLEXPART** dispersion model (EWS)

- Contrasting **FLEXPART-WRF** (**EWS**) ash simulations (**with/w-o Aeolus**).
- Evaluation of **FLEXPART-WRF** runs vs **ACTRIS Lidar** profiles.

Etna case study on 12 March 2021

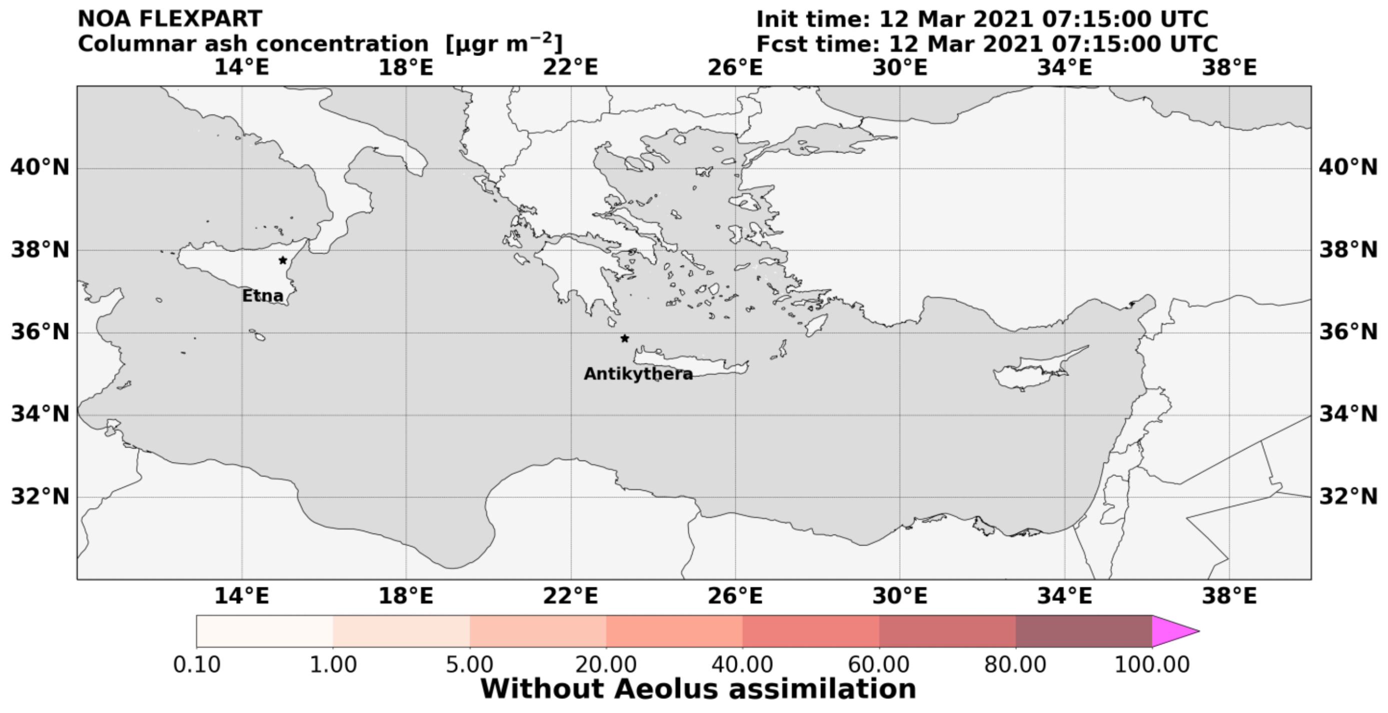


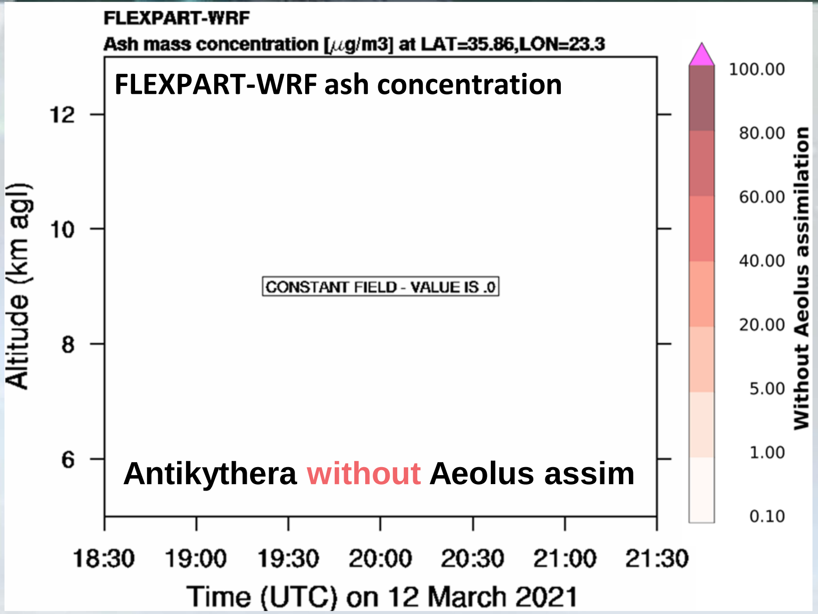


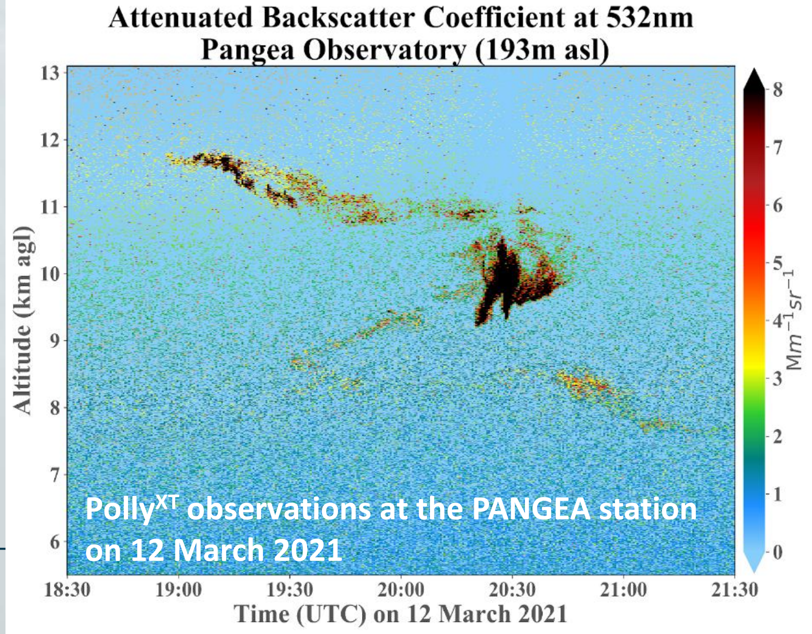
- Near-real time **alerts** from **Etna** volcano eruptions (**INGV observatory of Catania, Italy**).
- Volcanic cloud is moving eastwards crossing Antikythera and Limassol lidar stations.
- **Input data** of the **injection plume height** & **emission fields** (**in situ** & **satellite**); derived from **INGV** are used for the **initialization** of the operational **Early Warning System** at the PANGEA-NOA

Volcanic ash dispersion without Aeolus assimilation 12 March 2021

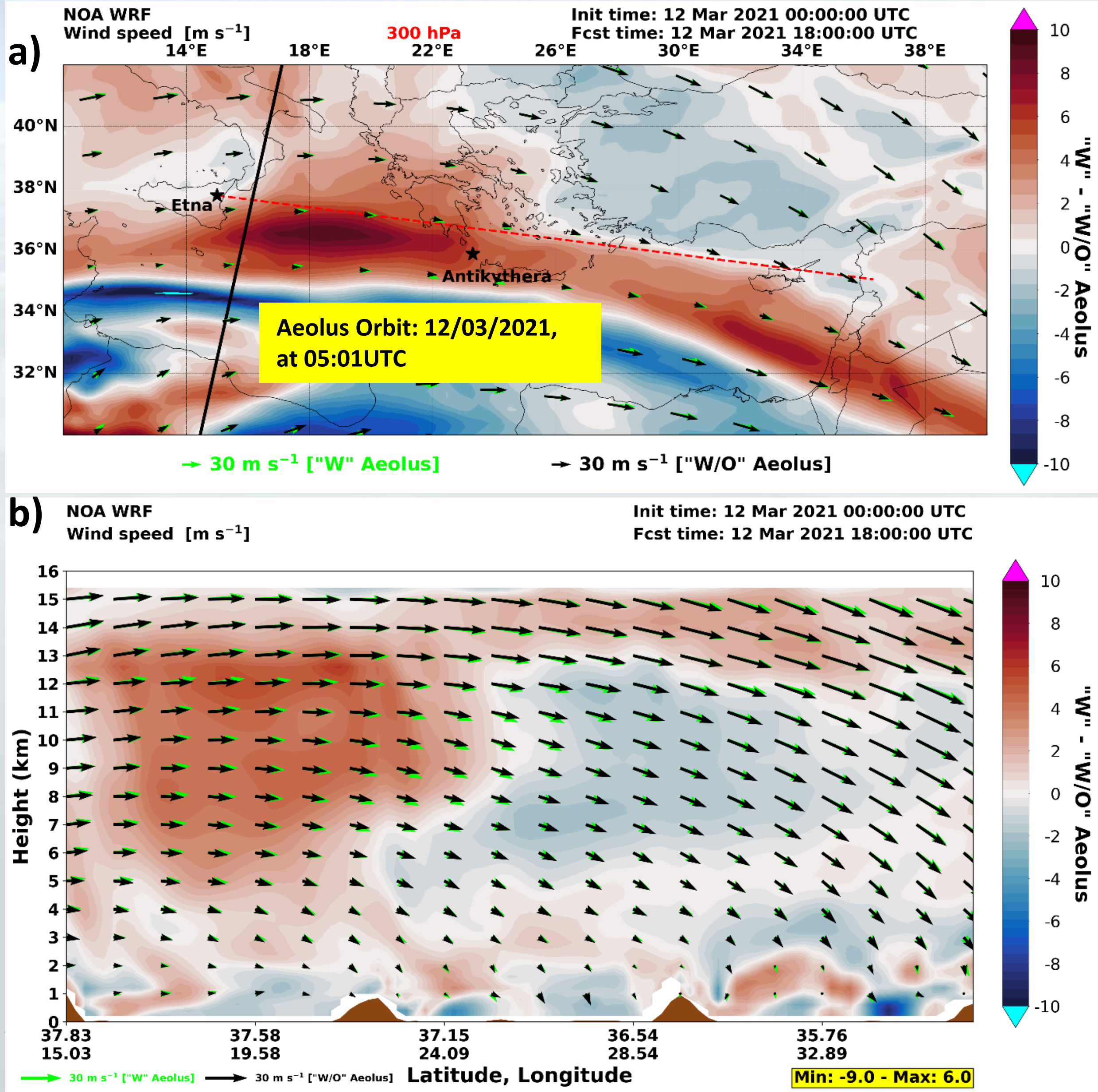
Control Run: FLEXPART-WRF Ash Simulation







Differences in wind fields with/w-o Aeolus assimilation - 300hPa



→ **With** Aeolus assimilation

→ **Without** Aeolus assimilation

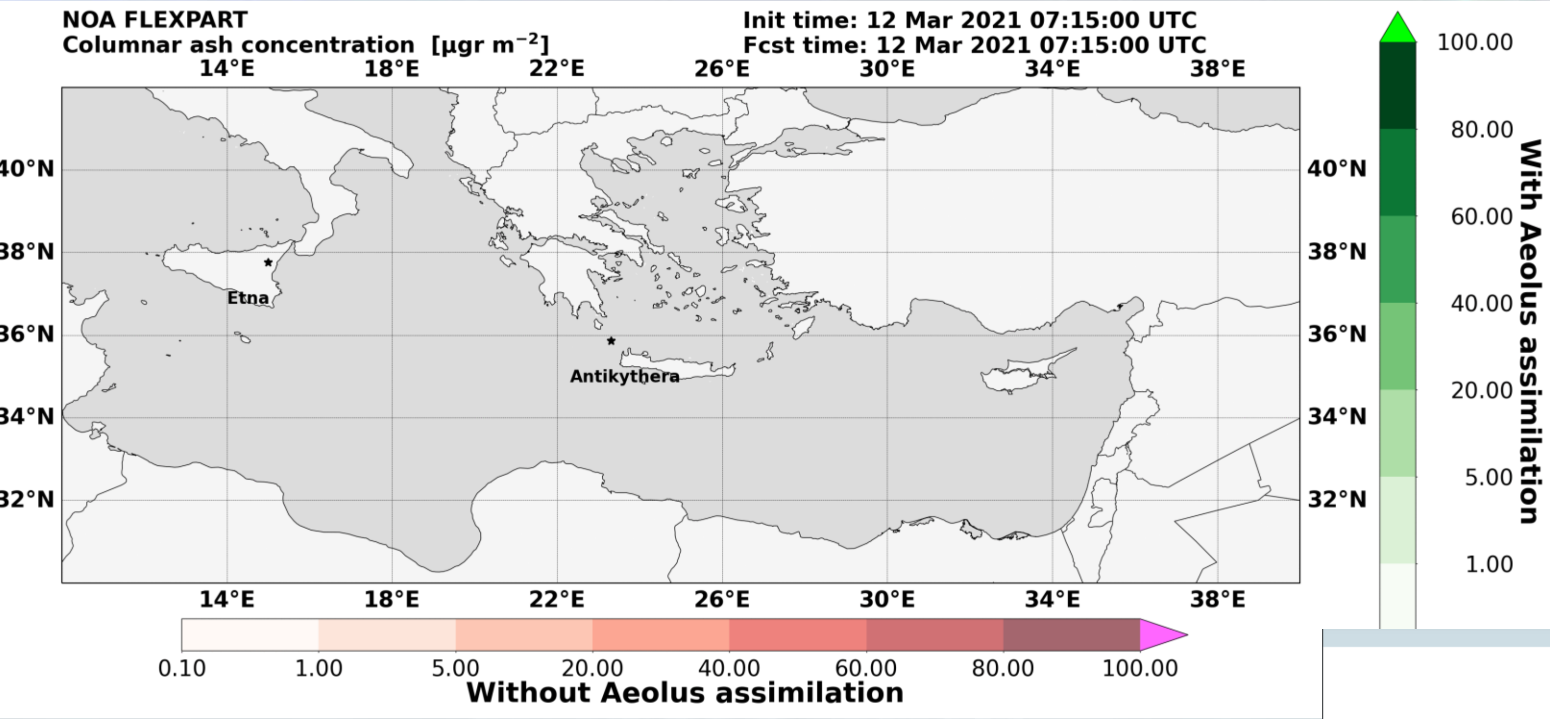
Upper panel:

- Prevailing **Westerly winds – Zonal activity** over the Mediterranean in the upper troposphere.
- **Positive differences** are evident along the pathway of the volcanic ash plumes.

Bottom panel:

- In the **vertical**, the effects of assimilation are mostly evident between **7-15 km** along the cross-section denoted with the dashed red line.

Volcanic ash dispersion with/w-o Aeolus assimilation 12 March 2021



- Volcanic ash plume **with Aeolus** assimilation arrives over Antikythera station on 12th March 2021, at 20:45UTC

- Expands southwards with respect to the **control run** (without Aeolus wind assimilation).

With Aeolus assimilation

Without Aeolus assimilation

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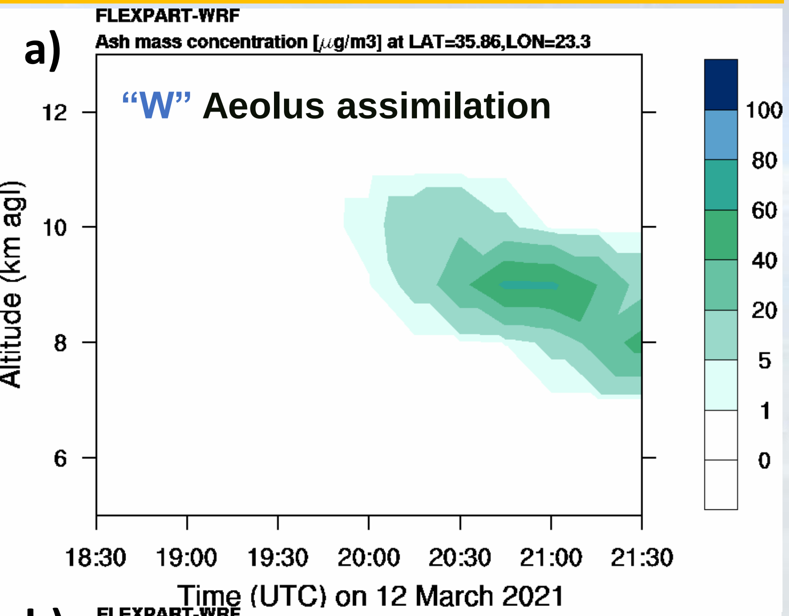
Aeolus winds impact on volcanic ash early warning systems for aviation

Vassilis Amiridis[1], Anna Kampouri[1,2], Antonis Gkikas[1], Stergios Misios[1], Anna Gialitaki[1,3], Eleni Marinou[1], Michael Rennie[4], Angela Benedetti[4], Stavros Solomos[5], Prodromos Zanis[2], Olympia Vasardani[6], Konstantinos Eleftheratos[6], Peristera Paschou[1,3], Thanasis Georgiou[1], Simona Scollo[7], Lucia Mona[8], Nikolaos Papagiannopoulos[8], Christian Retscher[9], Tommaso Parrinello[9] & Anne Grete Straume[10]

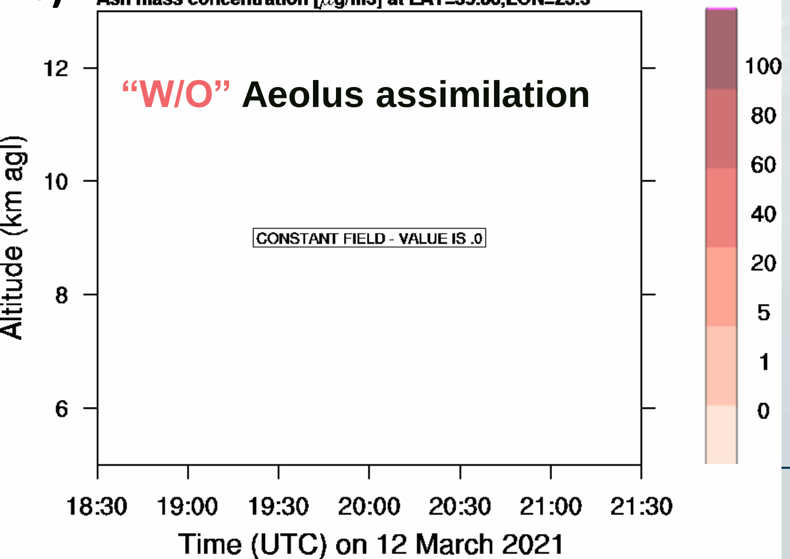
Vertical time-height cross-sections of volcanic ash distribution

FLEXPART-WRF with/w-o Aeolus

a)

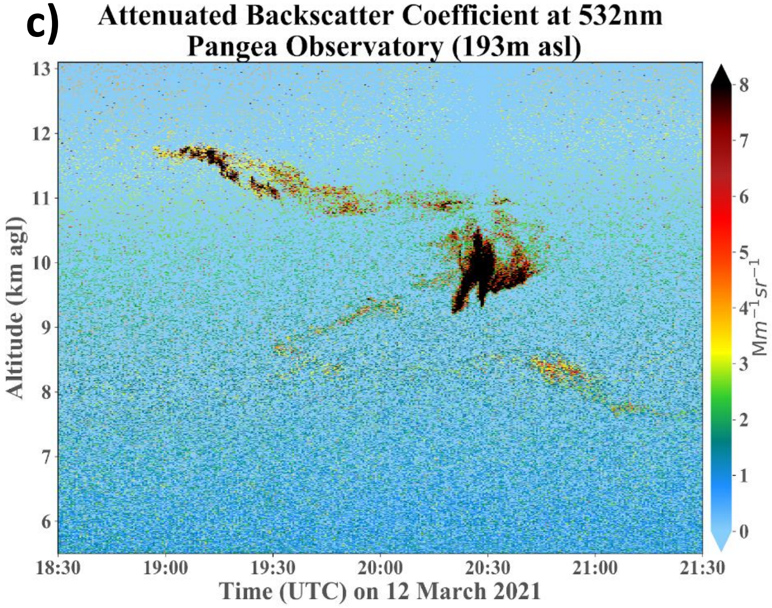


b)

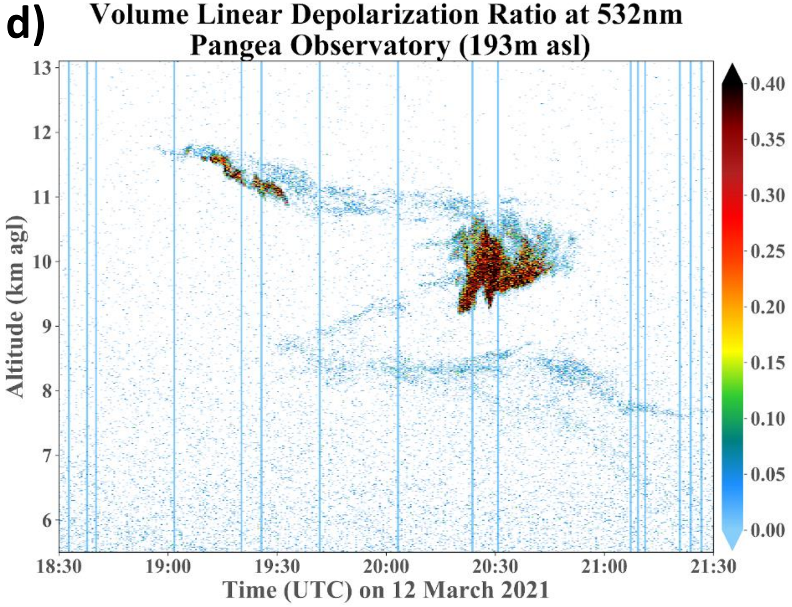


Polly^{XT} observations at PANGEA station on 12 March 2021

c)

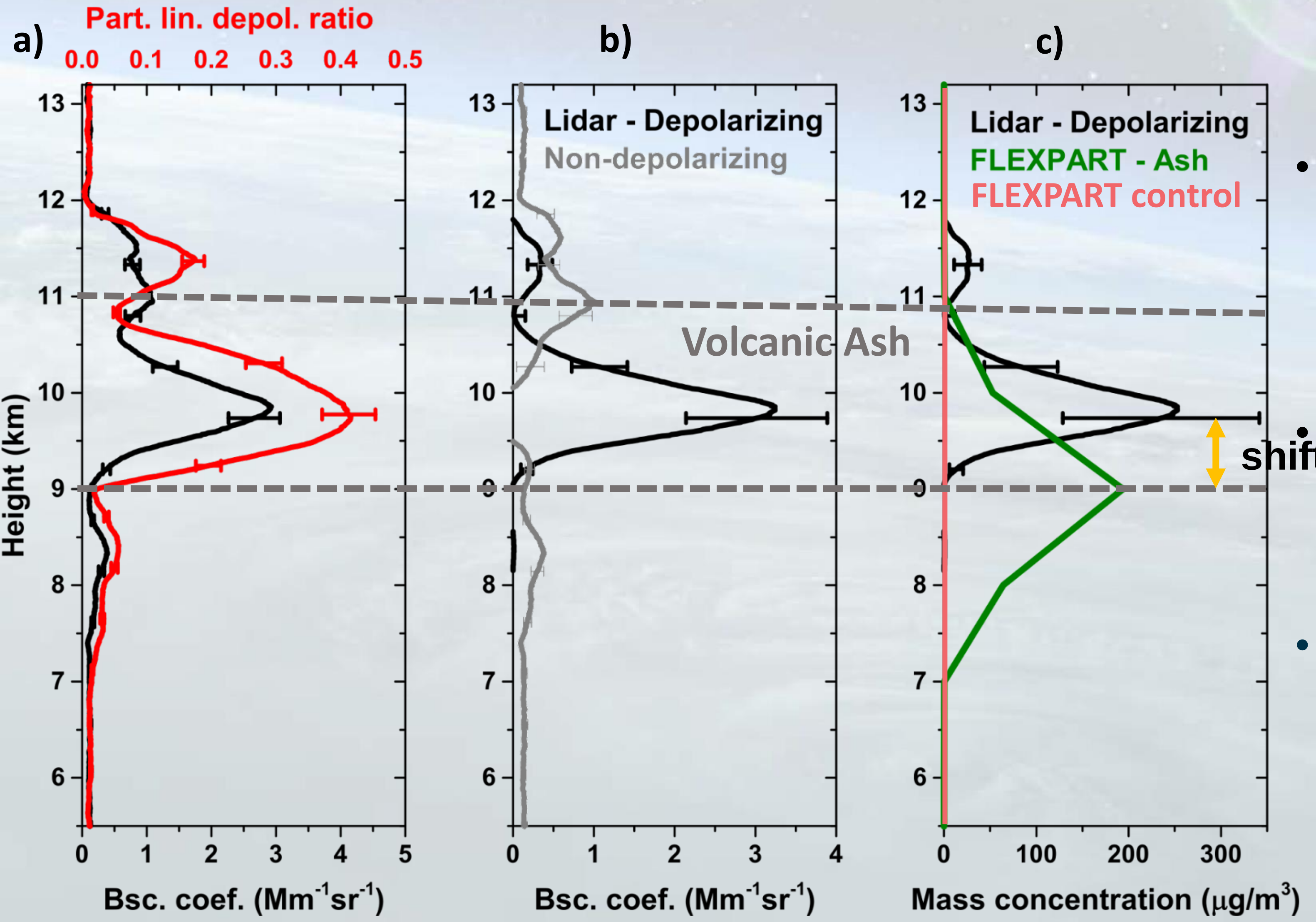


d)



Ash concentrations **a,b) w/w-o** Aeolus assimilation**, c)** the time-height curtain plot of the attenuated backscatter coefficient and **d)** volume linear depolarization ratio based of **Polly^{XT}-NOA lidar retrievals** at the PANGEA station during **12 March 2021** (18:30 to 21:30UTC).

Vertical profile of volcanic ash concentration above PANGEA-NOA station (from 18:30 to 21:30 UTC)



- **Ash concentrations** observed in the Polly^{XT} lidar are ***in good agreement*** with the model when Aeolus winds are assimilated (**c**).
- Despite ... run the concentrations are zero (**c** red line)

Need for better source emissions!!

- The ***observed and simulated*** mass concentration peaks are not well matched (**shift of 1km**)

Ongoing work and forthcoming actions

The impact of Aeolus on volcanic ash quantitative dispersion modeling by applying inversion techniques on Etna’s volcanic emissions

Inversion techniques

- Develop an **inverse modeling scheme** for estimating the **emission rates** of volcanic releases, from Etna volcanic eruption with FLEXPART-WRF model.
- The **inversion scheme** will be based on the theoretical work of (Stohl, et al., 2011) which was used to yield volcanic ash emission rates.

$\mathbf{M}_{(m\times n)}$ is a matrix of source-receptor sensitivities (SRR) calculated with **FLEXPART**

$\mathbf{y^o}_m$: is the vector of the m observed concentrations from **Polly^{XT} Lidar**

$\mathbf{x}_n$: is the vector of n=79 (unknown) **emission masses** at different heights in the source

$$y^o = M\,x$$

- **Initialize** the inversion simulations with $\mathbf{y^o}_m$ *mass concentrations* of ground-based **Polly^{XT} Lidar** combined with the outputs of $\mathbf{M}_{(m\times n)}$ **SRR FLEXPART** runs.
- Estimate Etna **volcanic emissions** at the source location.

Workflow

esa

Initial and boundary conditions

IFS outputs [ECMWF]

Exp1:

"w/o" Aeolus assimilation

Exp2:

"w" Aeolus assimilation

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WRF-ARW regional atmospheric model

Initialization of WRF-NOA

48 hours WRF forecast runs initialized with 2 sets of IFS outputs (**w/w-o Aeolus**) at 12 March 2021, 00:00 UTC (boundary conditions every 6 hours)

FLEXPART-WRF dispersion model

WRF meteorological fields **drive** **FLEXPART** dispersion model

FLEXPART SRR Sensitivities

Estimate M_w & $M_{w/o}$ (**FLEXPART SRR w/w-o Aeolus**)

Next step

Run Inversion algorithm: y^o = M x

- ✓ M_w and $M_{w/o}$: FLEXPART ***SRR*** "w/w-o" Aeolus
- ✓ y^o: POLLY^{XT} Lidar ***observations***
- ➢ **x:** source ***emissions***

FLEXPART SRR Sensitivities - Methodology

IFS outputs [ECMWF]

Exp1:

“w/o” Aeolus assimilation

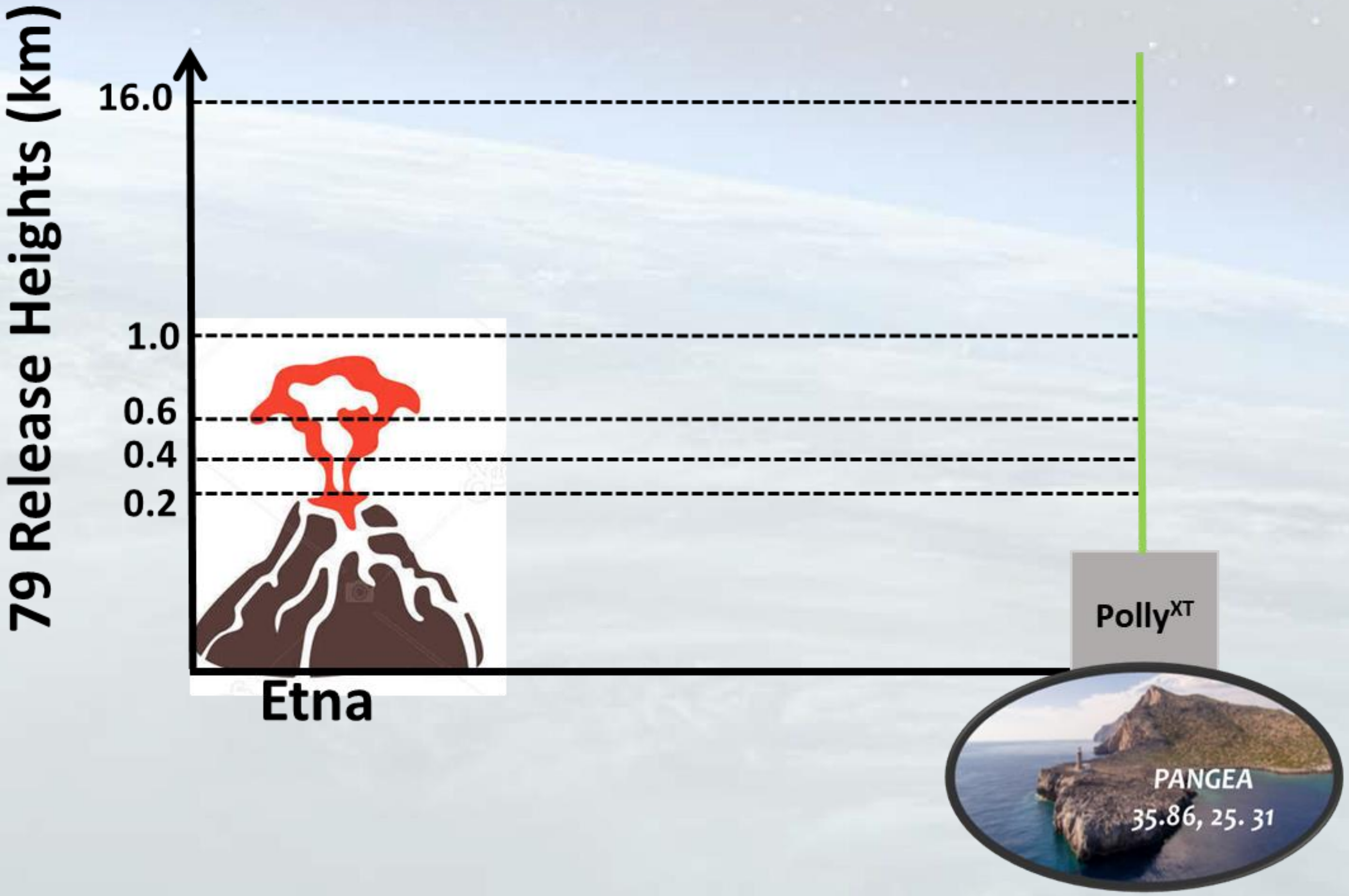
Exp2:

“w” Aeolus assimilation

FLEXPART-WRF (Stohl et al., 2005; Pisso et al., 2019) **forward runs** (simulation start: 12032021, 04UTC end: 14032021, 00UTC), initialized with the data from **ECMWF (“w/w-o”** Aeolus), for different **volcanic ash** sizes:

- **Ash1** : 3μm diameter
- **Ash2** : 5μm diameter
- **Ash3** : 9μm diameter
- **Ash4** : 21μm diameter

FLEXPART SRR Sensitivities - Methodology



Inversion Runs with Polly^{XT} Lidar retrievals

- **79 independent releases** above Etna at different heights (per 200m):
  - 150k particles/each
  - 1kg total mass

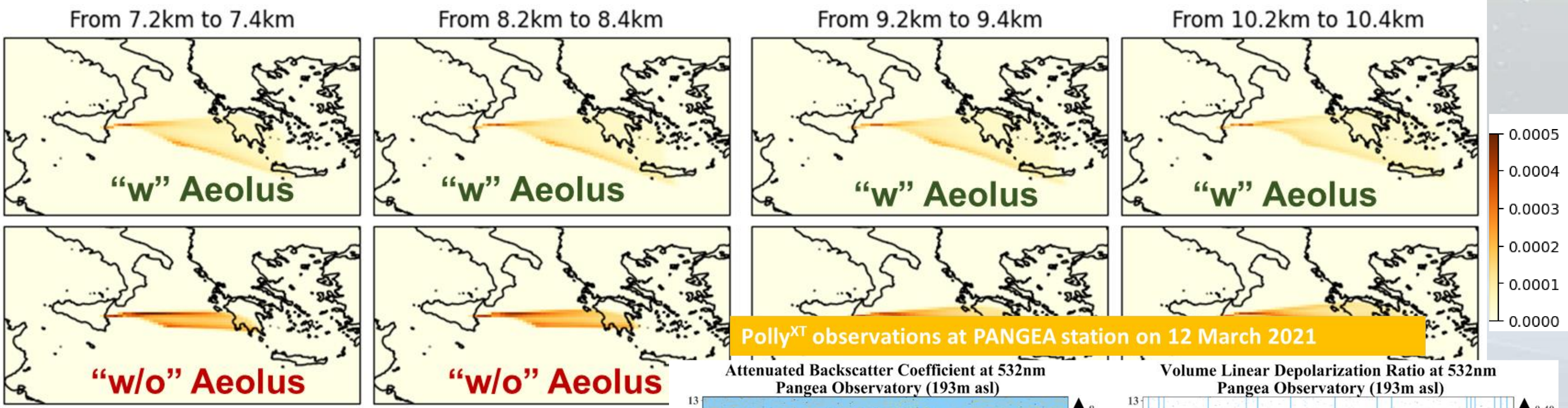
Repeated "w" and "w/o" Aeolus Assimilation

- 11 model levels:
  - 2 km vertical resolution between 4 km & above 22 km a.g.l,
  - a single layer between the surface & 4 km a.g.l.
  - Single layer from 22–50 km a.g.l.

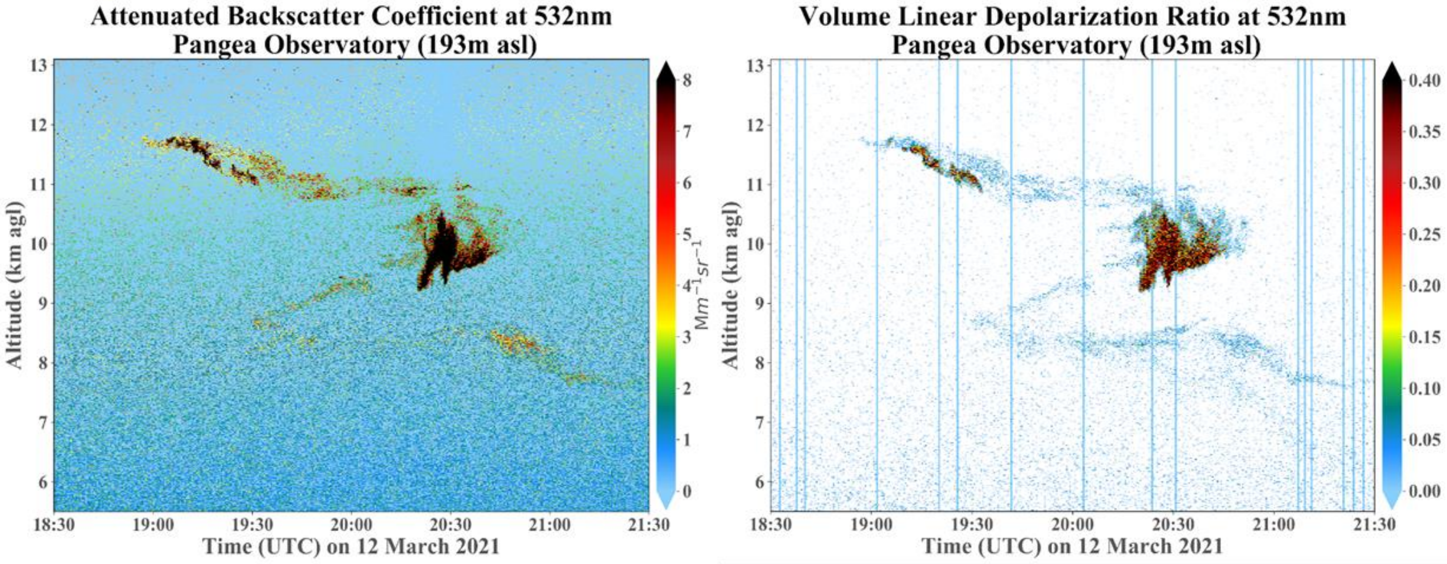
Determine the relationship between each emission height with each receptor height

FLEXPART SRR sensitivities above PANGEA-NOA station from 18:30 to 21:30 UTC

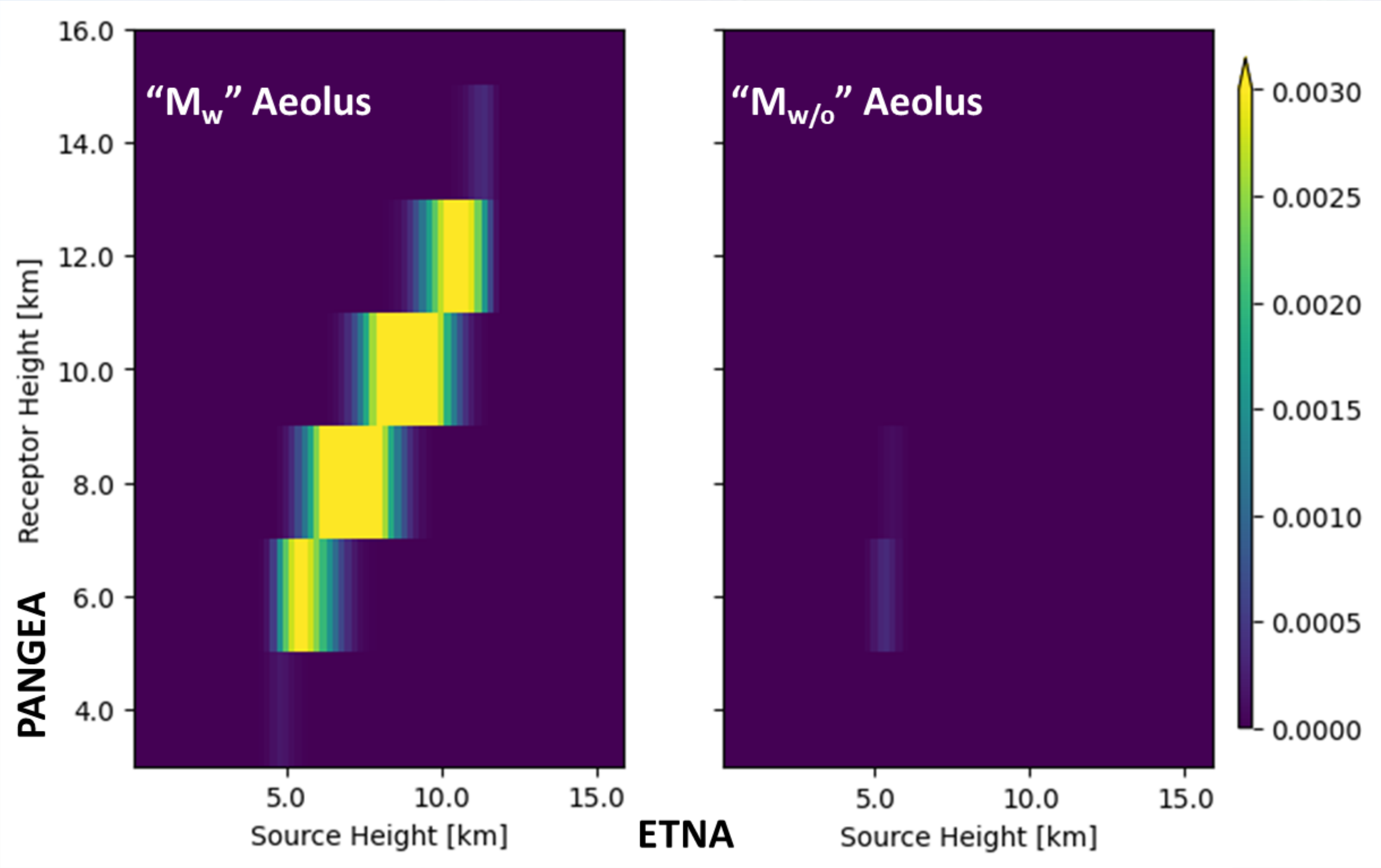
Examples of Ash dispersion **“w/w-o”** from different Etna Release heights



Polly^{XT} observations at PANGEA station on 12 March 2021



FLEXPART SRR sensitivities above PANGEA-NOA station from 18:30 to 21:30 UTC



$y^o = M x$

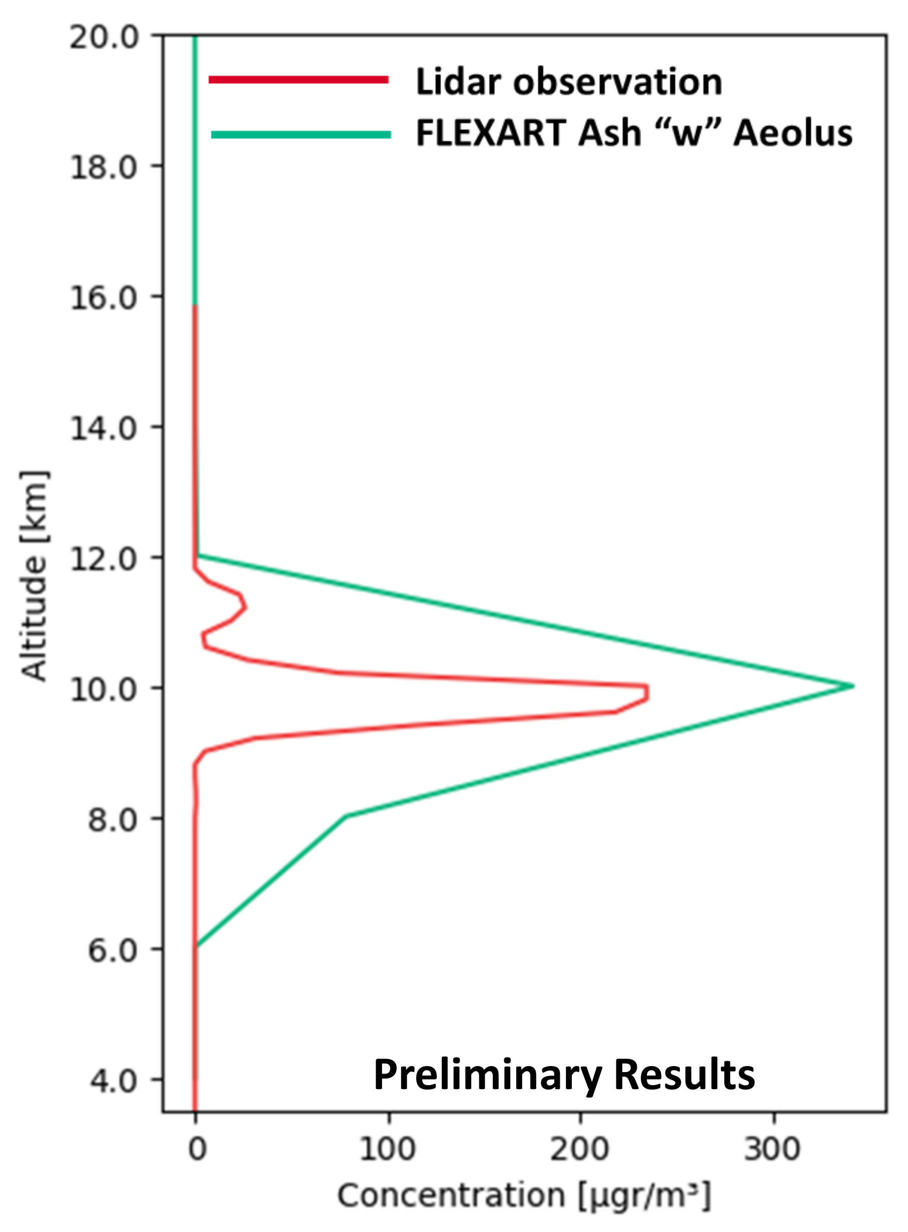
M_w & $M_{w/o}$
(FLEXPART SRR w/w-o Aeolus)

- To determine the **M_w & $M_{w/o}$** we run different **forward simulations** with unity mass at *79 different emission heights*.

➢ **"w" Aeolus SRR Sensitivity:**

<u>Source emissions</u> observed above PANGEA on 12 March 2021 (18:30 to 21:30UTC) *at heights* **7.5-12km** mostly deriving from Release heights between **6 to 12 km.**

Vertical profile of volcanic ash concentration above PANGEA-NOA station (from 18:30 to 21:30 UTC) after Inversion



$y^o = Mx$ — emission masses

y^o_m : observed concentrations from Polly^{XT} **Lidar**

M_w & $M_{w/o}$ (FLEXPART SRR w/w-o Aeolus)

- The **emission profile** obtained in the **inversion** was then used to simulate the transport of the plume.
- The **observed** and **simulated** *mass concentration peaks* ***are well matched*** (the vertical shift of 1km is vanished after inversion).
- **Better source emissions** provide **better vertical agreement** between observations and simulation.
- Ash concentrations observed in the Polly^{XT} lidar are *not so well reproduced* with the model.

Ongoing work and forthcoming actions

- **SRR Sensitivities "w" Aeolus** provides reasonable **Release heights** for the observed emissions above PANGEA station on 12 March 2021 (18:30 to 21:30UTC).

- More accurate Etna **emission rates** obtained after inversion method in **FLEXPART** model **"w" Aeolus** wind fields assimilation.

- The inversion algorithm **"w" Aeolus** data **optimizes** the ***vertical emission distribution.***

- Model Ash mass concentration *was not so well simulated* with respect to the Lidar observations.

Next steps

Further improvements of our the inversion scheme could include some of the following:

- Minimize the difference in mass concentration between simulated and observed Ash mass.
- Considering the time dimension in the algorithm to optimize the temporal emission distribution.
- Include gravitational settling of aerosol.
- Validate the algorithm with more observations from other Lidar stations.

Acknowledgements

NEWTON team acknowledges support by ESA in the framework of Aeolus+Innovation (ESA AO/1-9544/20/I/NS).

The research leading to these results was supported through the European Research Council (ERC) under the European Community's Horizon 2020 research and innovation framework programme – ERC grant agreement no. 725698 (D-TECT)

This research was supported by data and services obtained from the PANhellenic Geophysical Observatory of Antikythera (PANGEA) of the National Observatory of Athens (NOA), Greece

We acknowledge support of this work by the project "PANhellenic infrastructure for Atmospheric Composition and climatE change" (MIS 5021516) which is implemented under the Action "Reinforcement of the Research and Innovation Infrastructure", funded by the Operational Programme "Competitiveness, Entrepreneurship and Innovation" (NSRF 2014-2020) and co-financed by Greece and the European Union (European Regional Development Fund)

We acknowledge the support of Stavros Niarchos Foundation

We acknowledge the support by EU H2020 E-shape project (Grant Agreement n. 820852).

Surveillance system of Etna is operated by INGV-OE and we thank all technicians and technologists involved in their maintenance.

THANK YOU!!