Simulation of volcanic and fire ashes spectra with σ-IASI/F2N

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What is σ-IASI/F2N ?

σ-IASI/F2N is an **all sky fast pseudo mono-chromatic radiative transfer tool** designed to cover the spectral range spanning from **NIR** to **FIR** (**3-100 μm**).

The main characteristics of this code are:

1. **Fast computation time** (~ 0.8 s average for 1 high resolution spectra);
2. **Computation of analytical Jacobians** necessary for the application in inverse scheme;
3. **Suitable spectral resolution** thanks to convolution with IRF of different instrument.

Atmospheric state,
Configuration file (input by the user)

Extinction due to gaseous components
(Look-up-Table)

$C_{ilm}(\nu)$

Extinction due to particle interaction
like clouds and aerosol (Look-up-Table)

$\beta(\nu, r_e), \omega(\nu, r_e), b(\nu, r_e)$
$\boldsymbol{k}(r_e)$

Continuum absorption
(MT-CKD, CIA)

$R(\upsilon, T), C_s(\upsilon, T)$

Computation of high resolution
transmittance

Computation of high resolution radiances

Masiello et all., 2024
https://doi.org/10.1016/j.jqsrt.2023.108814

How is the interaction with particles treated in σ-IASI/F2N?

The idea is to preserve the original equations utilized for the clear sky scenario by applying a scaling approximation to take into account the multiple scattering from clouds or aerosols layers (Chou et al., 1999).

Clear sky scenario:

$$R_\nu = R_{d,\nu} + R_{a,\nu} + R_{r,\nu} + R_{s,\nu}$$

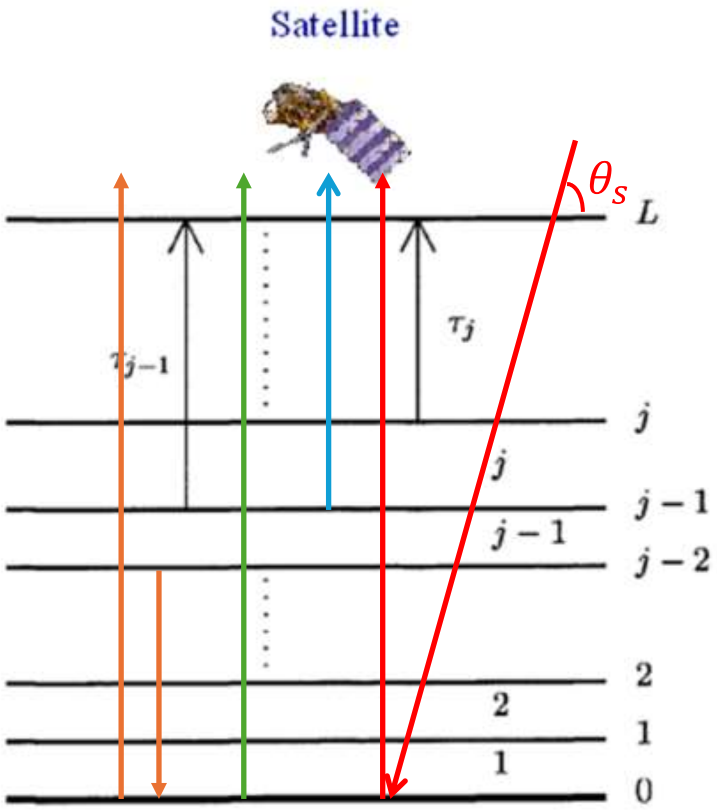
$$R_{d,\nu} = \varepsilon_\nu B_\nu(T)\tau_{0,\nu}$$

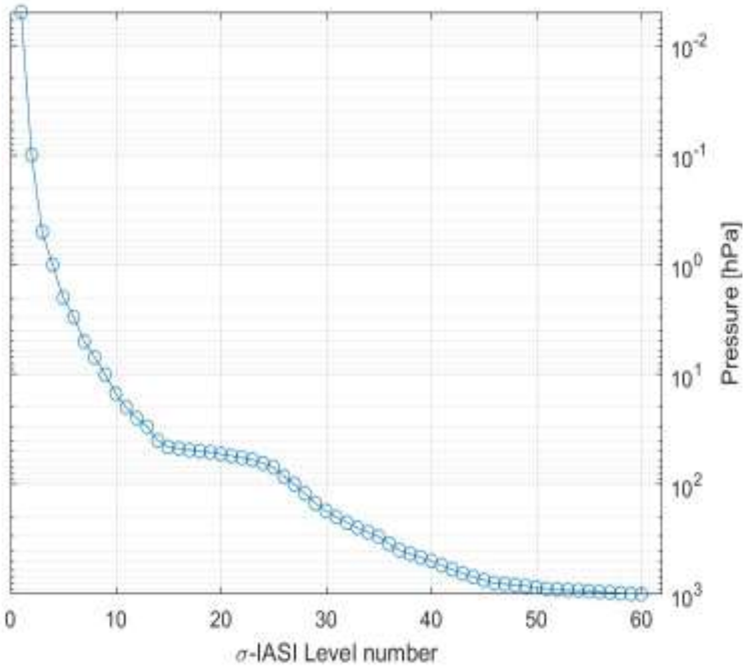
$$R_{a,\nu} = \sum_{j=1}^{L} B_\nu(T)(\tau_{\nu,j} - \tau_{\nu,j-1})$$

$$R_{r,\nu} = (\varepsilon_\nu - 1)\tau_{0,\nu}{}^2 \sum_{j=1}^{L} B_\nu(T)(\tau_{\upsilon,j}{}^{-1} - \tau_{\upsilon,j-1}{}^{-1})$$

$$R_{s,\nu} = (1 - \varepsilon_\nu)\frac{S_0}{\pi}\mu_s\tau_0\tau_0(\theta_s)$$

$$\tau_{\upsilon,j} = \prod_{0}^{j} \exp[-(OD_{gas,\nu})]$$





How is the interaction with particles treated in σ-IASI/F2N?

The idea is to preserve the original equations utilized for the clear sky scenario by applying a scaling approximation to take into account the multiple scattering from clouds or aerosols layers (Chou et al., 1999).

In presence of particles (clouds, aerosols):

$$R_\nu = (1 - f)R_{\nu,clear} + fR_{\nu,cloud}$$

$$R_{\nu,clear/cloud} = R_{d,\nu} + R_{a,\nu} + R_{r,\upsilon} + R_{s,\nu}$$

$$R_{d,\nu} = \varepsilon_\nu B_\nu(T)\tau_{0,\nu}$$

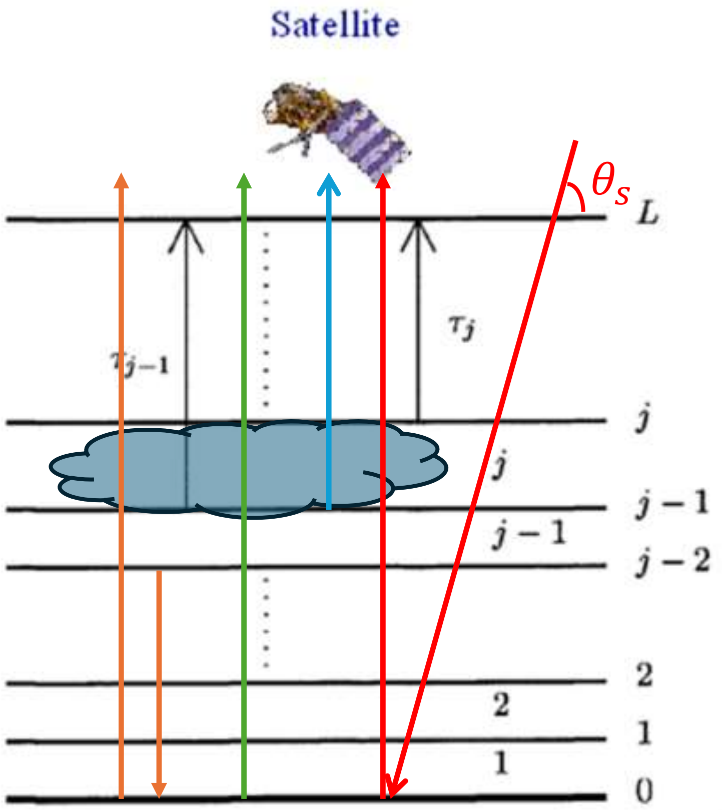
$$R_{a,\nu} = \sum_{j=1}^{L} B_\nu(T)(\tau_{\nu,j} - \tau_{\nu,j-1})$$

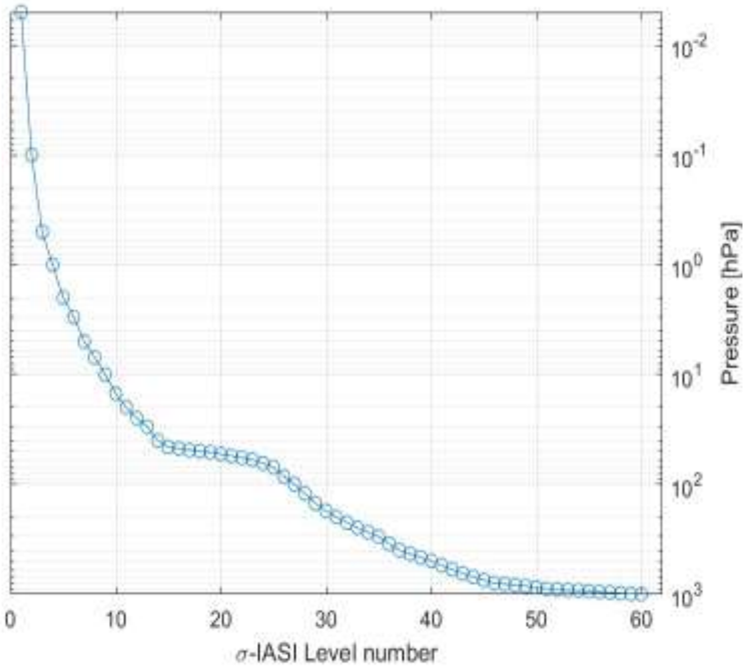
$$R_{r,\nu} = (\varepsilon_\nu - 1){\tau_{0,\nu}}^2 \sum_{j=1}^{L} B_\nu(T)({\tau_{\upsilon,j}}^{-1} - {\tau_{\upsilon,j-1}}^{-1})$$

$$R_{s,\nu} = (1 - \varepsilon_\nu)\frac{S_0}{\pi}\mu_s\tau_0\tau_0(\theta_s)$$

$$\tau_{\upsilon,j,clear} = \prod_{i=j+1}^{j} \exp[-(OD_{gas,\nu})]$$

$$\tau_{\upsilon,j,cloud} = \prod_{i=j+1}^{j} \exp[-(OD_{gas,\nu} + \boldsymbol{OD_{part,\nu}})]$$





Computation of the optical depth for particles – physical quantities

According to Chou scaling approximation, with some additional, manipulation we can obtain the OD as:

$$\frac{OD_{part,\nu}}{\Delta Z} = \frac{3}{2}\frac{xwc}{D_e \rho_x}\tilde{\beta}$$

$$\tilde{\beta} = \beta((1-\omega) + \omega b)$$

- xwc, D_e, ρ_x are physical quantities related to that specific particle;
- β, ω, b are optical properties related to the type of particles;

How do we get this variables and parameters?

Let's start from the simplest one, the physical quantities:

- **Mass over air volume of particles**

$$xwc = \rho_x \int_{L_{min}}^{L_{max}} V(l)n(L)dL = q_x \rho_a \qquad [xwc] = \frac{kg}{m^3}$$

ρ_a = atmospheric density = p/TR_a $\qquad [\rho_a] = \frac{kg}{m^3}$

q_x = particles mass mixing ratio $\qquad [q_x] = \frac{kg}{kg}$

- **Effective dimension of particles**

$$D_e = \frac{3}{2}\frac{\int_{L_{min}}^{L_{max}} V(L)n(L)dL}{\int_{L_{min}}^{L_{max}} A(L)n(L)dL}$$

$n(L)$ probability density distribution of particles; $V(L)$ volume of particles of size L; $A(L)$ projected area of a particles of size L

- **Particles density ρ_x**

Different for each type of particle

Computation of the optical depth for particles – optical properties

According to Chou scaling approximation, with some additional manipulation, we can obtain the OD as:

$$\frac{\boldsymbol{OD_{part,\nu}}}{\boldsymbol{\Delta Z}} = \frac{\boldsymbol{3}}{\boldsymbol{2}}\frac{\boldsymbol{xwc}}{\boldsymbol{D_e \rho_x}}\widetilde{\boldsymbol{\beta}}$$

$$\widetilde{\boldsymbol{\beta}} = \boldsymbol{\beta}((\boldsymbol{1}-\boldsymbol{\omega}) + \ \boldsymbol{\omega b})$$

- $\boldsymbol{xwc}, \boldsymbol{D_e}, \boldsymbol{\rho_x}$ are physical quantities related to that specific particle;
- $\boldsymbol{\beta}, \boldsymbol{\omega}, \boldsymbol{b}$ are optical properties related to the type of particles;

How do we get this variables and parameters?

1. Starting from the complex refractive index we generate single particle optical properties computing the Mie solution. The main properties we are interested in are:
   - $\boldsymbol{Q_{ext}}$ extinction efficiency;
   - $\boldsymbol{Q_{abs}}$ absorption efficiency;
   - $\boldsymbol{P}(\boldsymbol{\mu}, \boldsymbol{\phi}, \boldsymbol{\mu}', \boldsymbol{\phi}')$ Phase function;

Martinazzo et all., 2021
https://doi.org/10.1016/j.jqsrt.2021.107739

2. From single particle properties we move to bulk properties assuming realistic PSD for each type of particle.

$$\beta = \langle Q_{ext} \rangle = \frac{\int_{L_{min}}^{L_{max}} \boldsymbol{Q_e}(\boldsymbol{L}) A(L) n(L) dL}{\int_{L_{min}}^{L_{max}} A(L) n(L) dL}$$

$$\omega = \frac{\int_{L_{min}}^{L_{max}} (\boldsymbol{Q_e}(\boldsymbol{L}) - \boldsymbol{Q_a}(\boldsymbol{L})) A(L) n(L) dL}{\int_{L_{min}}^{L_{max}} A(L) n(L) dL}$$

$$b = \frac{1}{2}\int_0^{2\pi} \frac{1}{2\pi} d\phi \int_0^{2\pi} \frac{1}{2\pi} d\phi' \int_1^0 d\mu \int_{-1}^0 \boldsymbol{P}(\boldsymbol{\mu}, \boldsymbol{\phi}, \boldsymbol{\mu}', \boldsymbol{\phi}') d\mu'$$

3. The Bulk properties are then fitted with a 6th degree polynomial form of the effective radius as follow :

$$Y = \sum_{i=1}^{7} a_i x^{i-1}; x = \frac{1}{r_e + t}$$

Final form of the bulk optical properties

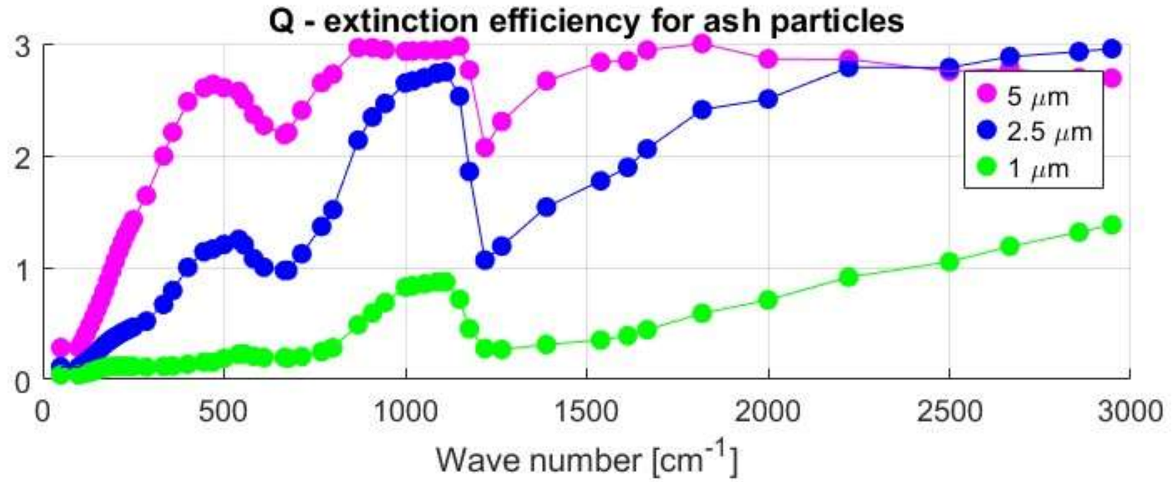
We report here two examples for the optical properties computed for volcanic ash particles and soot particles

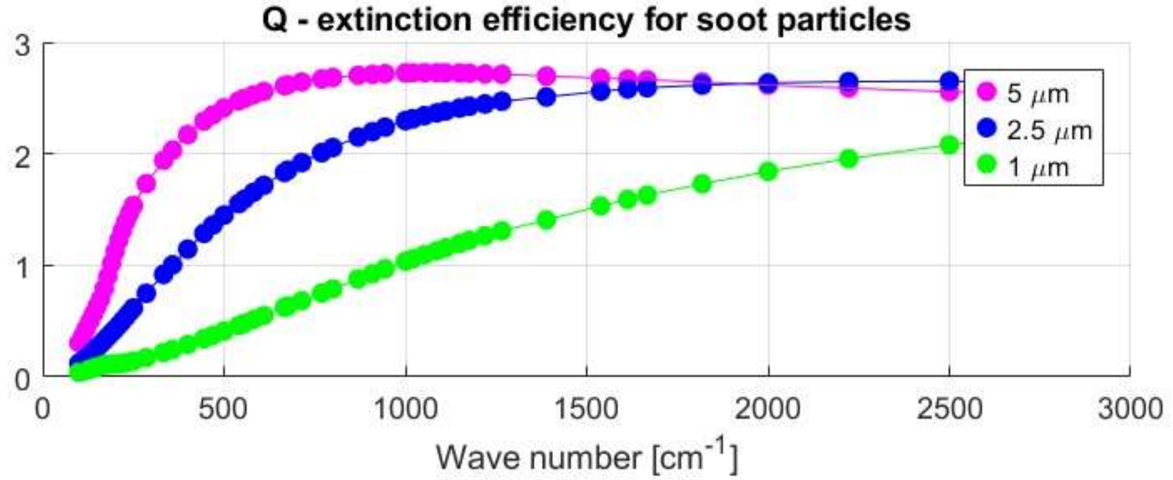
1. **Ash particles**

- Log normal distribution with $\sigma = 0.53$;
- Refraction index from Volz, Frederic E. 1973 (https://doi.org/10.1364/AO.12.000564);

2. **Soot particles**

- Log normal distribution with $\sigma = 0.69$;
- Refraction index from Twitty et al. 1971, ‘Radiative Properties of Carbonaceous Aerosols’.





Some application and our case of studies

- Volcanic ash:

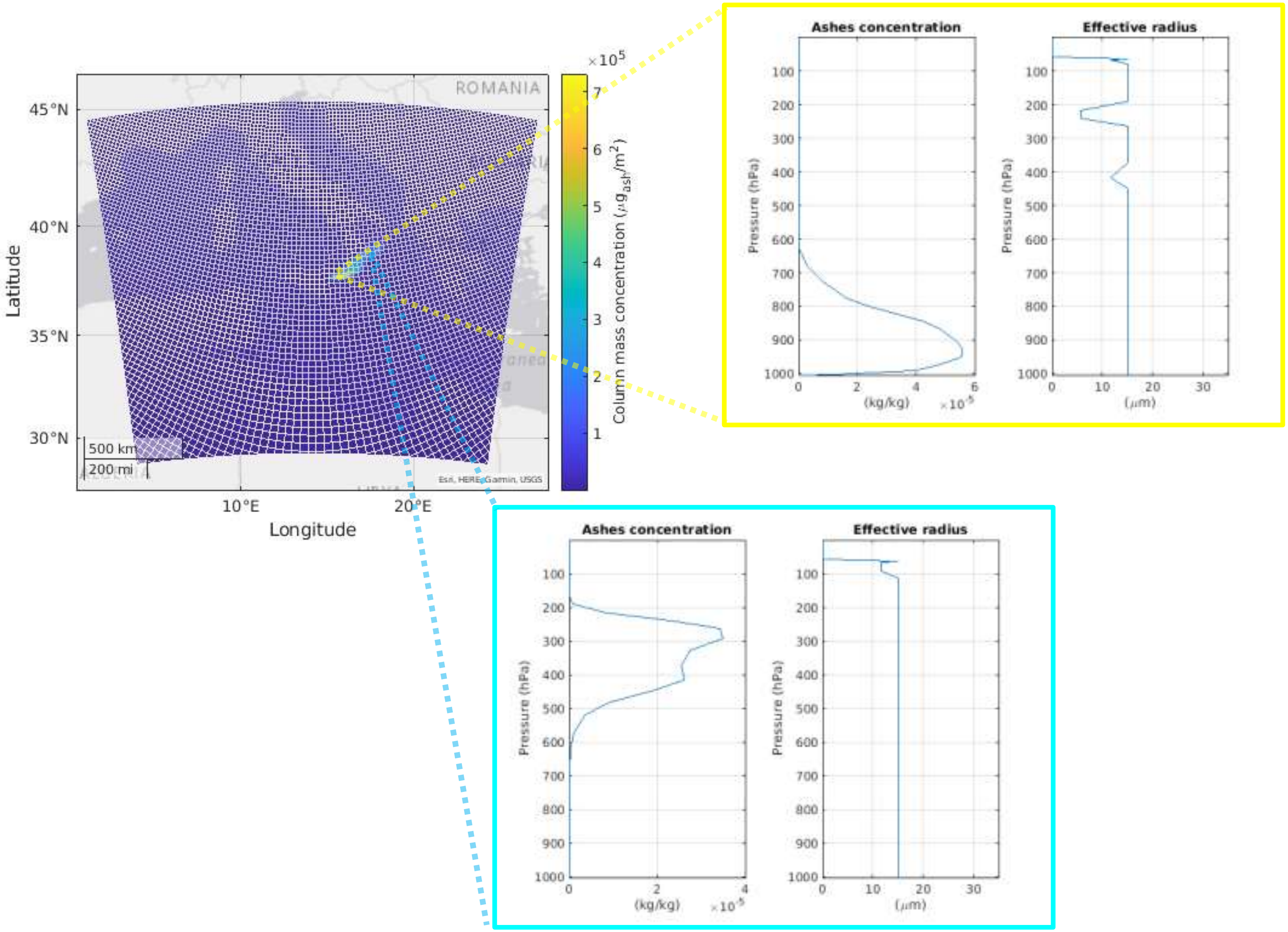
  Etna eruption, 23 November 2013;

- Forest Fire:

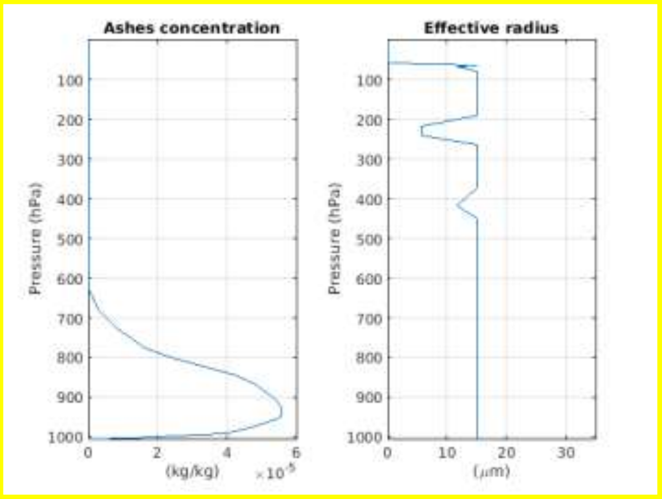
  Greece, Alexandroupolis, 21-27 August 2023

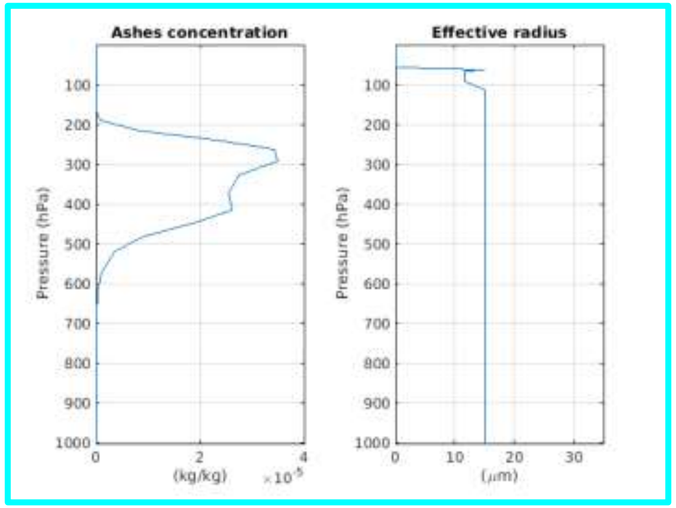
1st case - Simulation of Etna volcano eruption, 23 November 2013

The event has been simulated via WRF-chem on grid composed by 219 X 249 pixels spanning latitudes values in between the 28°-45° N and longitudes values from 3°-25°. Each pixel provides, on 39 vertical pressure level, the mass mixing ratio $(\mu g/kg_{dry\ air})$ distribution in function of the particle size. The spatial resolution is 6 km with slight variations across the domain due to curvature effects.

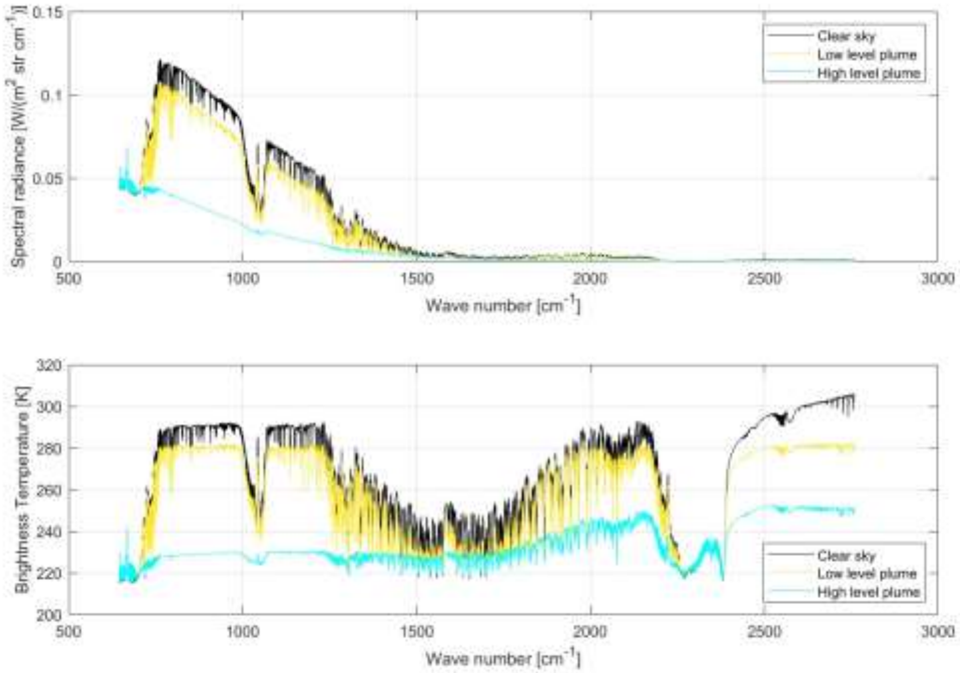


IASI like radiance computation



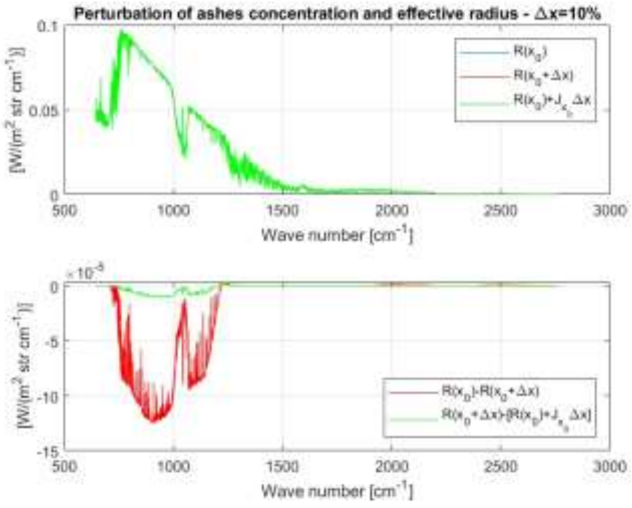


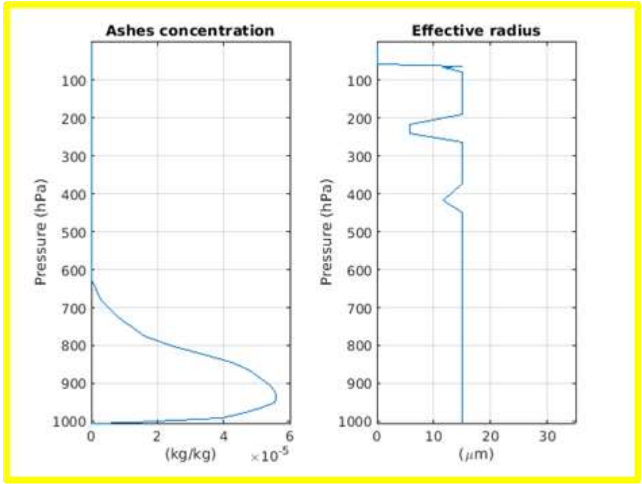
- Vertical distribution of ashes provided from WRF;
- Gas concentration obtained from climatological data of the area;
- Spectral interval simulated: 645 – 2760 cm^{-1};
- Spectral sampling: 0.25 cm^{-1};
- Effective radius is chosen starting from the mass concentrations distribution in each layer.

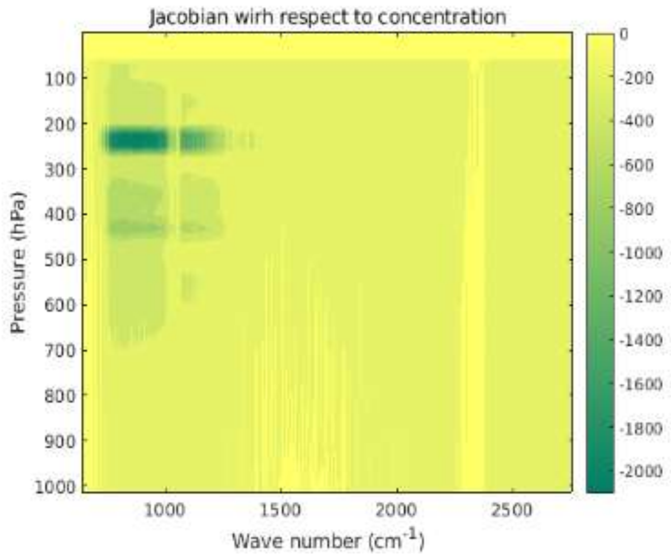


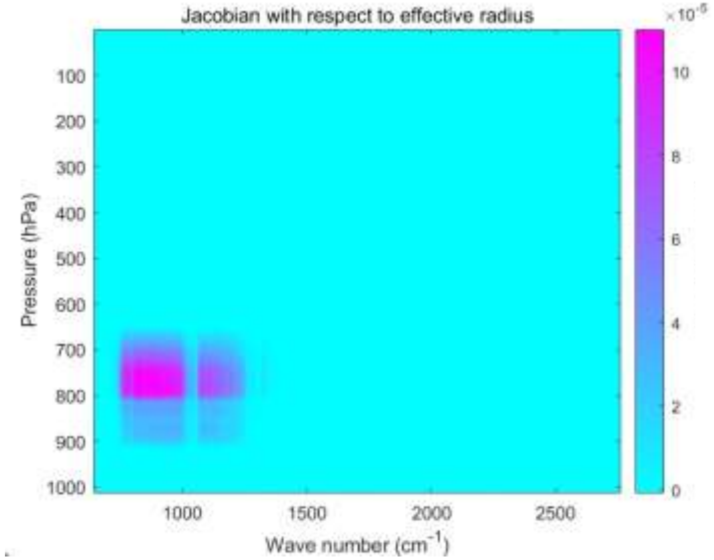
Self consistency through Jacobian computations and linearity test

- Thanks to the aerosols' optical properties parametrization, we're able to compute analytical Jacobians on each level of the simulation;
- The consistency of these results have been verified thanks to linearity test;
- Analytical Jacobians computation will allow to utilize **σ-IASI/F2N** to retrieve ash vertical profile and concentration.





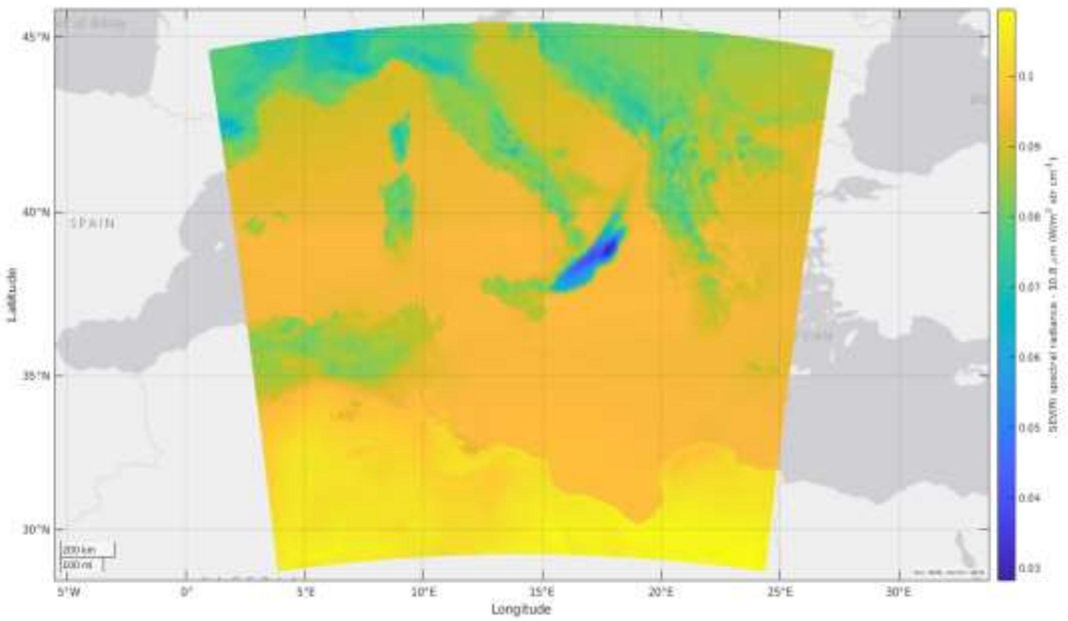




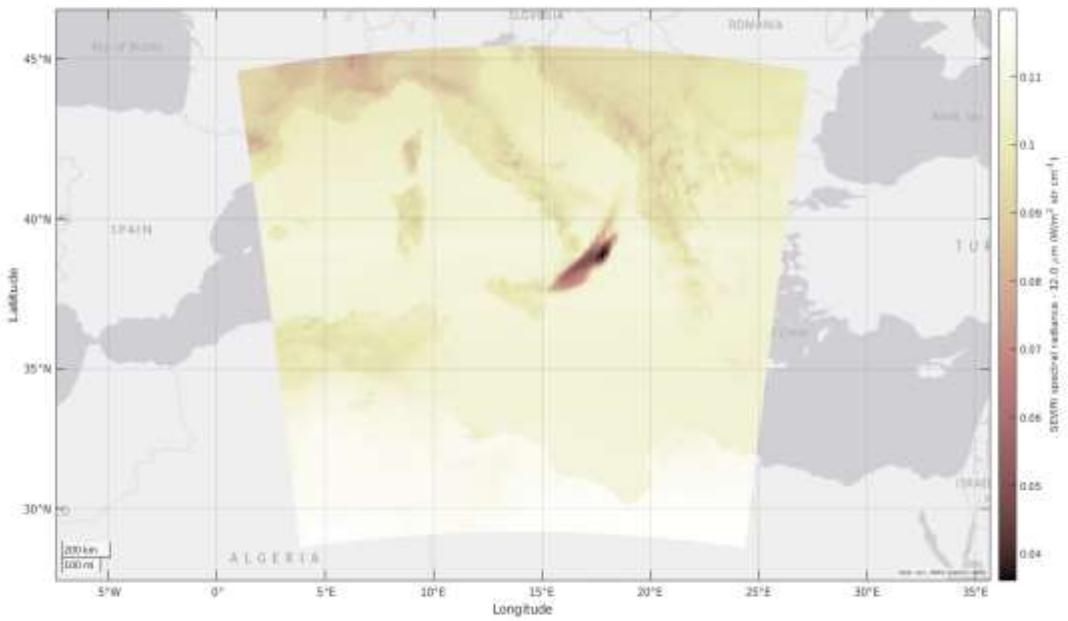
Convolution with SEVIRI IRF

The complete spectral information can also be downscaled to a lower spectral resolution through the convolution with the instrumental response function of other instrument like SEVIRI. This reproduce the eight channels present in the spectral range of our simulation which can be plotted on a latitude-longitude map highlighting areas affected from volcanic ash.

SEVIRI CHANNEL - 10.8 μm



SEVIRI CHANNEL - 12 μm

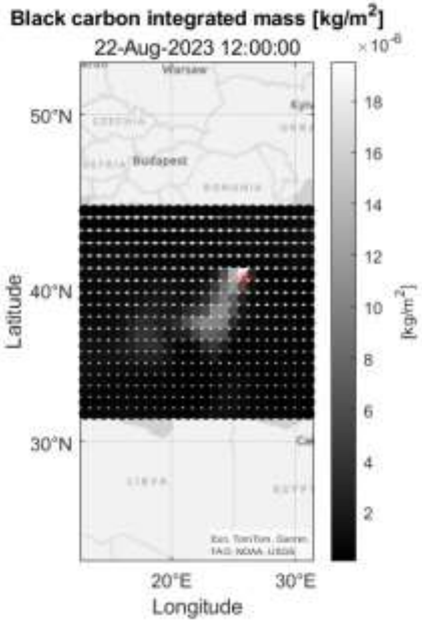


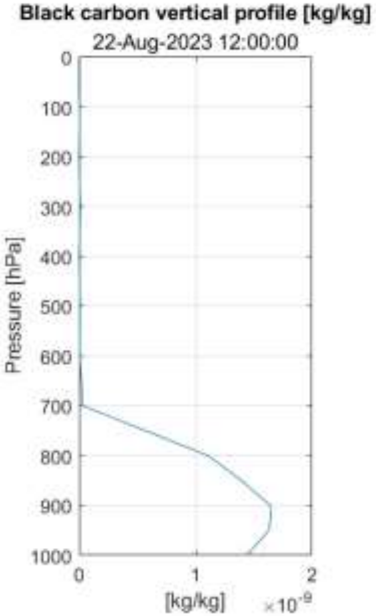
2nd case – analyses of Alexandroupolis forest fire, 21-27 August 2023

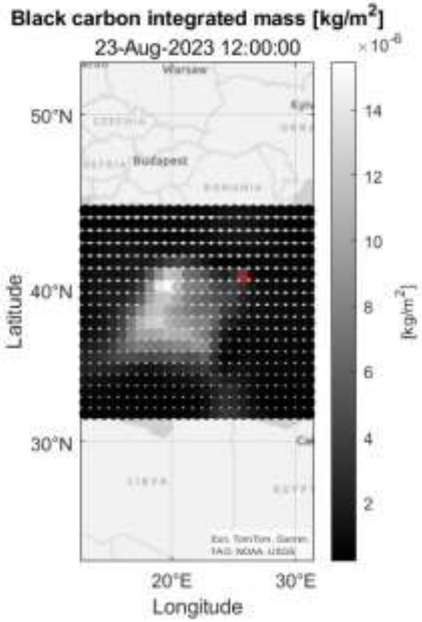
This particular event has been one of the most intense of the last year fire season in Greece with an estimated burnt area of 5775 ha (EFFIS). The atmospheric gaseous components and black carbon concentration related to this event have been collected through Copernicus service CAMS global atmospheric composition forecast on a 0.4°x0.4° horizontal grid and 25 vertical level.

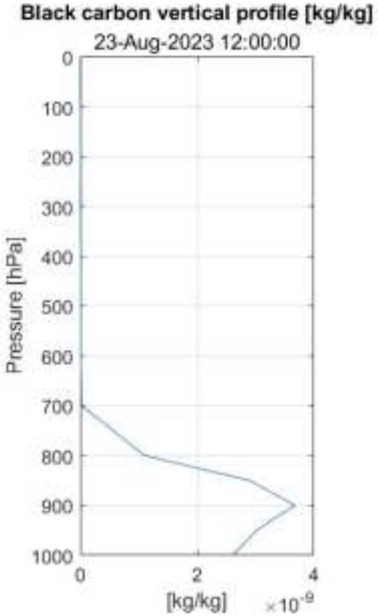
MODIS Terra satellite images:

- Left 22 August 2023 9:00
- Right 23 August 2023 9:00



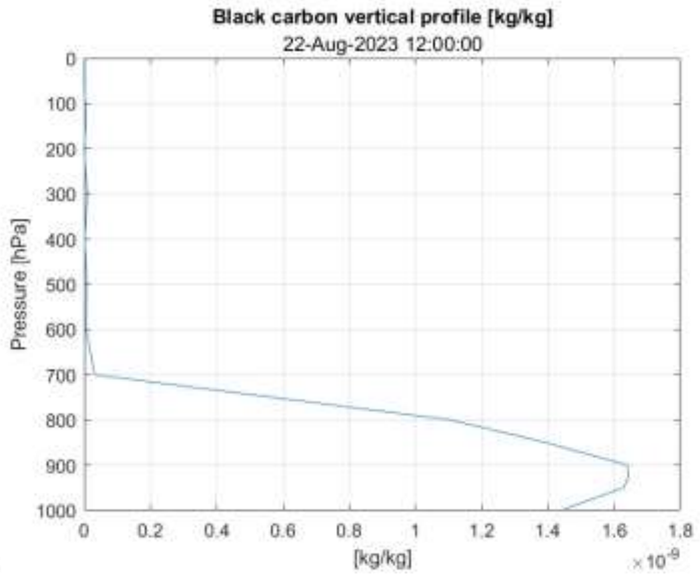


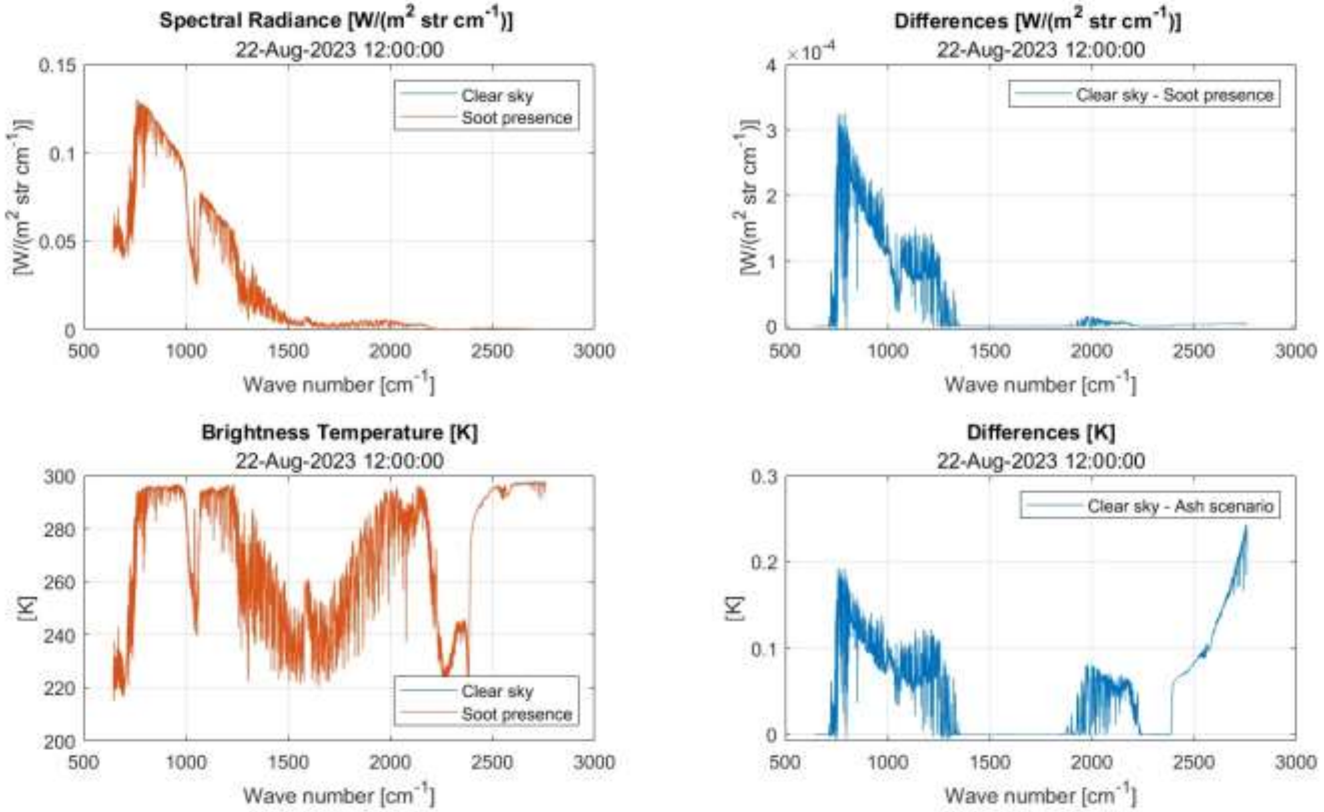




IASI like radiance computation

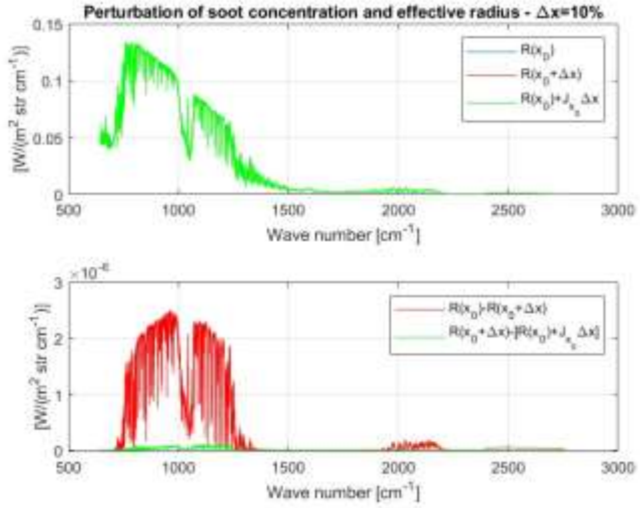
- Vertical distribution of black carbon is obtained from CAMS global atmospheric composition forecast;
- Gas concentration obtained from CAMS global atmospheric composition forecast;
- Spectral interval simulated: 645 – 2760 cm^{-1};
- Spectral sampling: 0.25 cm^{-1};
- Effective radius fixed to 1 μm;

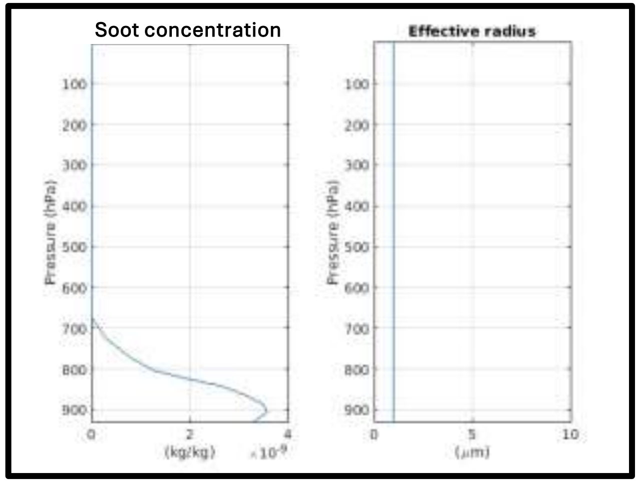


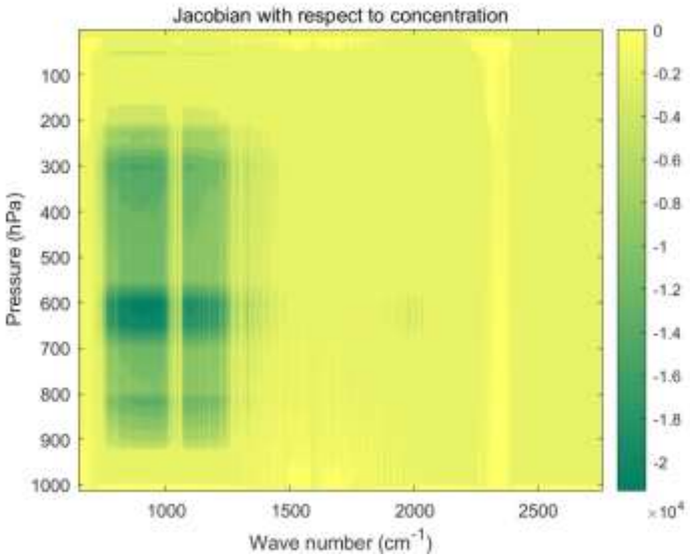


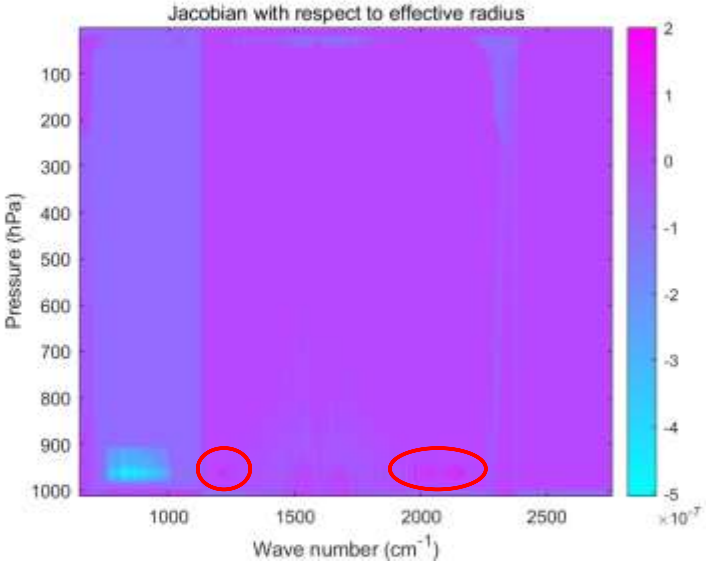
Self consistency through linearity test and Jacobians computations

- As for volcanic ash, self consistency of the results have been verified thanks to linearity tests and analytical Jacobians computation.
- Analytical Jacobians computation will allow to utilize **σ-IASI/F2N** to retrieve soot vertical profile and concentration.









CONCLUSION

- We have applied the Chou approximation, which has already been proven effective for meteorological clouds and cirrus clouds, also to aerosols particles such as volcanic ash and forest fire soot;
- We have demonstrated that we are able to compute analytical Jacobians and correctly reproduce variations into the particles profile and effective dimensions;
- We have shown that we are able to compute IASI like radiances in all-sky condition retaining the same computational efficiency of the clear sky condition.

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THANK YOU!