Retrievals of sulphur species from IASI measurements

Elisa Carboni[1] (elisa@atm.ox.ac.uk), Lucy Ventress[2], David England[1], Isabelle Taylor[1,3], Tamsin Mather[3], Roy Grainger[1].

(1) COMET, AOPP - Physics, University of Oxford, United Kingdom, (2) NCEO, AOPP - Physics, University of Oxford, United Kingdom ,(3) COMET, Earth Sciences, University of Oxford, UK.,.

Abstract:
Volcanic eruptions are a significant source of atmospheric SO2 and its effects and lifetime depend on the SO2 injection altitude.
In the stratosphere, SO2 oxidizes to form stratospheric H2SO4 aerosol that can affect climate for several years.
The effects of SO2 in the atmosphere and the speed of conversion into H2SO4 depend on the amount released and on the altitude of the plume.
Thermal infrared spectra are affected by both SO2 and H2SO4 droplets and can be used to both quantify and study the conversion.
Here we exploit the high resolution nadir spectral measurements from IASI for SO2 and H2SO4 retrievals and we present:
1) the results of the SO2 retrieval (Carboni et al. 2012, Carboni et al 2016), of column amount and altitude (vertical distribution), for recent eruptions.
2) A new optimal estimation aerosol retrieval scheme for H2SO4, together with sensitivity study and error analysis.

(1) linear retrieval (detection) theory

[Rodger 2000]

The optimal estimate of x taking into account total measurement error may be computed as:

$$\hat{\mathbf{x}} = \mathbf{x}_0 + \underbrace{(\mathbf{K}^T \mathbf{S}_y^{\text{tot}\,-1} \mathbf{K})^{-1} \mathbf{K}^T \mathbf{S}_y^{\text{tot}\,-1}}_{\mathbf{G}} (\mathbf{y} - \bar{\mathbf{y}})$$

$$\mathbf{G} = (\mathbf{K}^T \mathbf{S}_y^{\text{tot}\,-1} \mathbf{K})^{-1} \mathbf{K}^T \mathbf{S}_y^{\text{tot}\,-1}$$

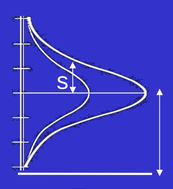
Create a generalized error covariance Sy^{tot} that contains not only the instrument noise, but noises due to interfering gases and broadband scatterers (using IASI spectra only).

S_y^{tot} is computed considering an appropriate ensemble of N measured spectra to construct an estimate of total measurement error variance-covariance S_y^{obs}

$$\mathbf{S}_y^{\text{tot}} \approx \mathbf{S}_y^{\text{obs}} = \frac{1}{N} \sum_{i=1}^{N} (\mathbf{y}_i - \bar{\mathbf{y}})(\mathbf{y}_i - \bar{\mathbf{y}})^T \qquad \bar{\mathbf{y}} = \frac{1}{N} \sum_{i=1}^{N} \mathbf{y}_i$$

[Walker, Dudhia, Carboni, Atmos. Meas. Tech., 2011]

OE Retrieval scheme - iterative



SO2 State vector:
- Total column amount of SO_2
- Altitude H
- ~~Thickness s~~
- Surface temperature Ts

Aerosol State vector:
- AOD at 550nm
- Effective radius
- Altitude H
- Surface temperature Ts

+ ECMWF profile (temperature, h2o, p, z)

F(x) — Forward model: fast radiative transfer (RTTOV + SO2 RAL coefficients)

IASI simulated spectra

IASI measurements → OE retrieval

y is the measurement vector, **x** the state vector, **F(x)** forward model, **Sy** error covariance matrix

$$J = (y - F(x))^T S_y^{-1} (y - F(x)) + (x - x_a)^T S_a^{-1} (x - x_a)$$

best estimate of stare vector:

$S_y(i,j) = \langle (y_{mi} - y_{si}) - \overline{(y_{mi} - y_{si})} \rangle \langle (y_{mj} - y_{sj}) - \overline{(y_{mj} - y_{sj})} \rangle$

$y_s = F(SO_2=0)$ — Sy Computed with billions pixels

Sy, is defined to represent the effects of atmospheric variability not represented in the forward model (FM), as well as instrument noise (cloud and trace-gases…).
The matrix is constructed from differences between FM calculations (for clear-sky) and actual IASI observations for wide range of conditions, when we are confident that negligible amounts of SO2 are present.

SO_2 linear

Retrieve: SO2 column amount [DU]

Assume: SO2 vertical profile

(Walker et al 2011, 2012)
NRT products assuming:
0-20, 0-2, 4-5, 9-10, 14-15, 19-20km

$S_y(i,j) = \langle (y_{mi} - \overline{y_{mi}}) \rangle \langle (y_{mj} - \overline{y_{mj}}) \rangle$

Very fast !!

New: products assuming:
200, 400 mb

Aerosol linear

Retrieve: Ash optical depth (AOD) at 550nm

Assume: Ash altitude, Effective radius (Reff = 2 micron)

SO_2 OE

Retrieve: SO2 column amount [DU], SO2 plume altitude [mb, km]

Require auxiliary data (ECMWF profiles), radiative transfer (RTTOV) called iteratively

$S_y(i,j) = \langle (y_{mi} - y_{si}) - \overline{(y_{mi} - y_{si})} \rangle \langle (y_{mj} - y_{sj}) - \overline{(y_{mj} - y_{sj})} \rangle$

Medium/slow speed (~2000 ch)

(Carboni et al 2012, 2016)

Aerosol OE

Retrieve: AOD (550nm), Reff [micron], Ash plume altitude [mb, km]

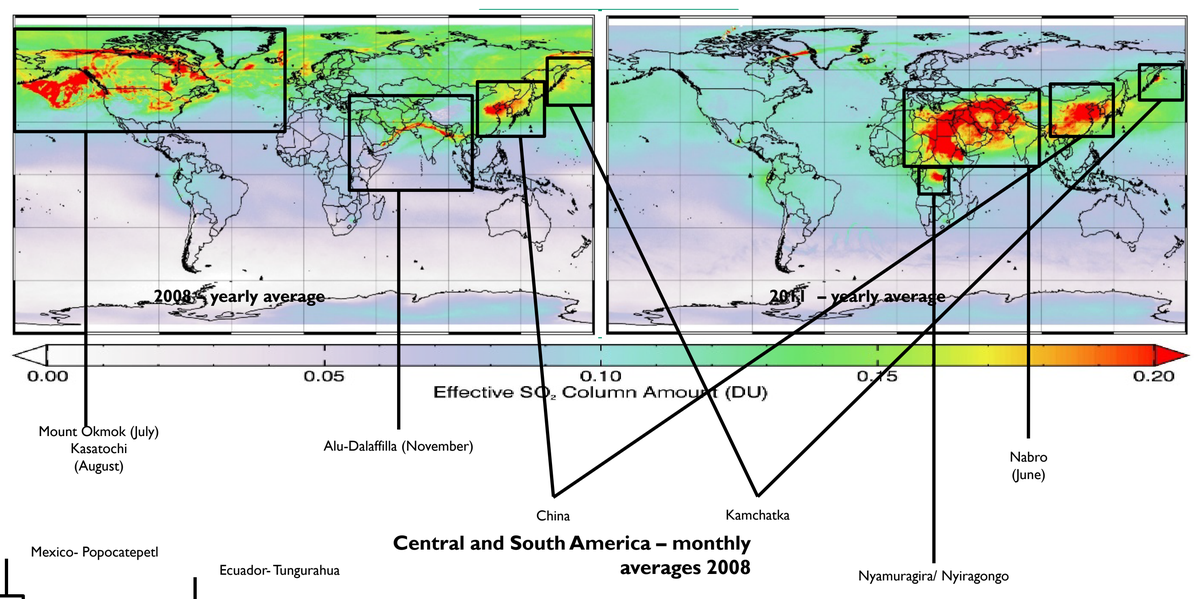
Medium speed (~100 ch)

Totally new, in development

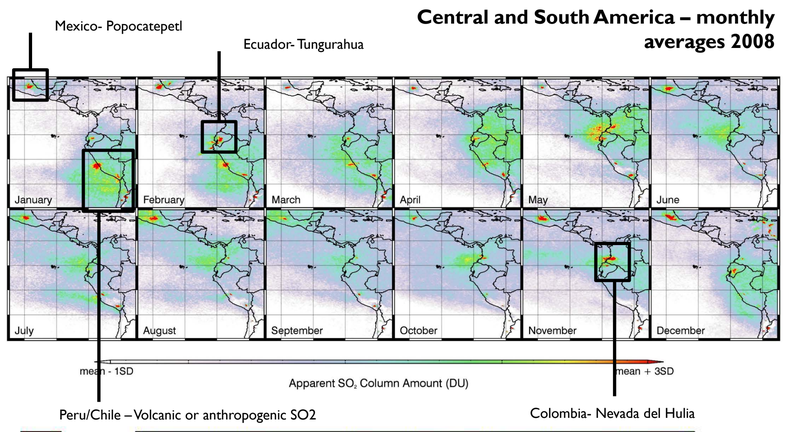
comprehensive error budget for every pixel

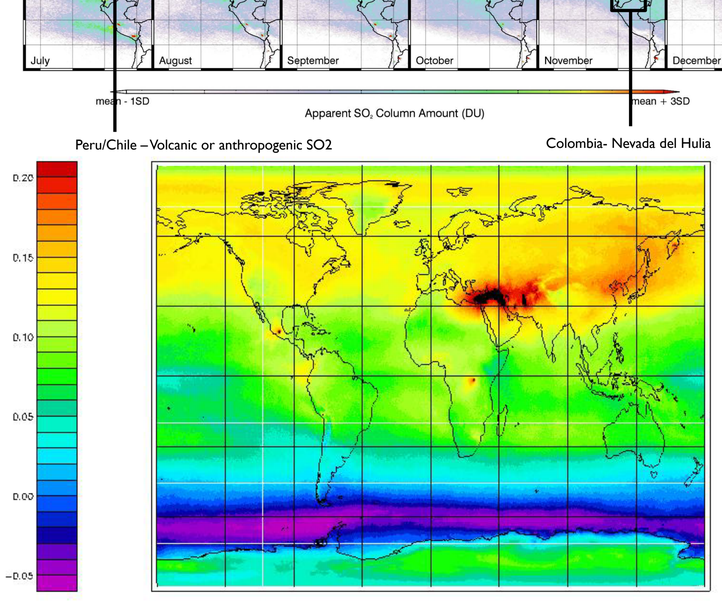
SO_2 linear retrieval

- All IASI archive 2007-2016 analysed
- IASI NRT data processing
http://www.nrt-atmos.cems.rl.ac.uk/



Central and South America – monthly averages 2008



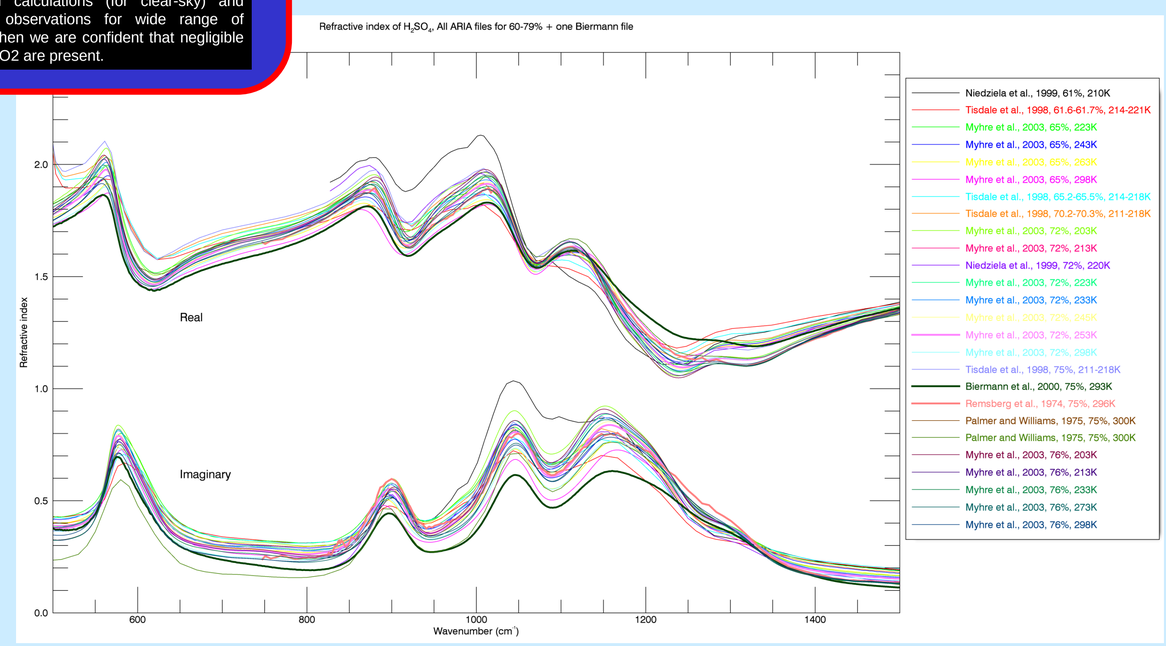


Here, the 'fast' linear retrieval has been applied across the globe to detect volcanic sources of SO2. The results are dominated by emissions from explosive eruptions, but signals are also evident from weak eruptions, passive degassing, and anthropogenic activity.

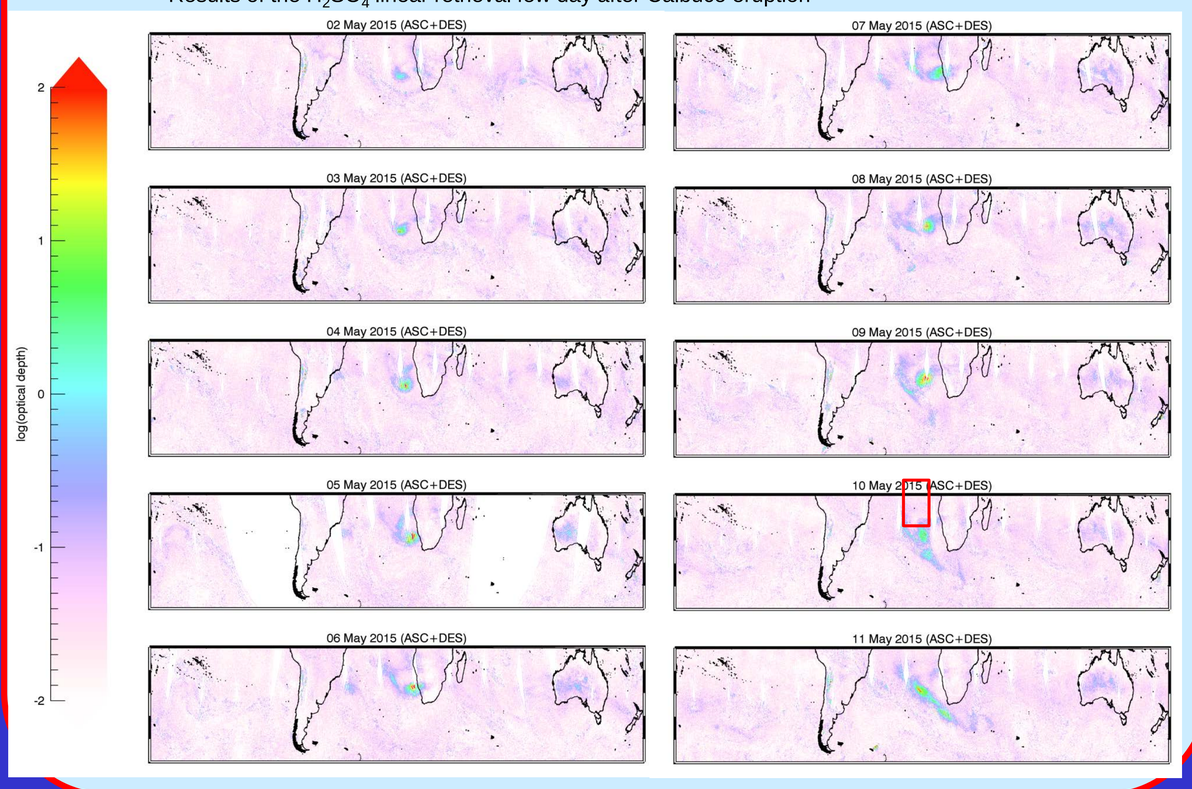
Average of the SO2 linear retreival using an uniform SO2 profile between 0 and 20 km, for the JJA of 'non volcanic' years: 2007, 2010 2012, 2013, 2014

H_2SO_4 linear retrieval

H_2SO_4 droplets present different values in literature as a function of mixing ratio and temperature, we used Biermann et al 2000.

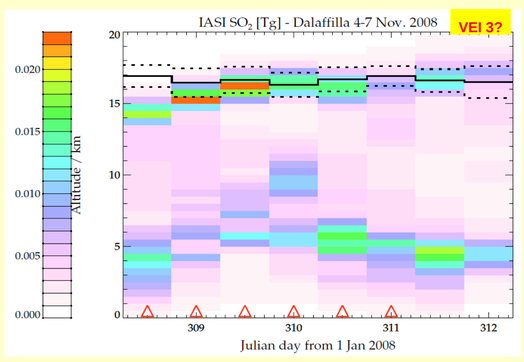


Results of the H_2SO_4 linear retrieval few day after Calbuco eruption

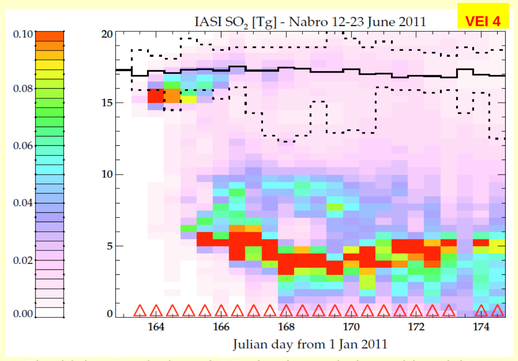


SO_2 OE - iterative

The colour represents the total mass of SO2 in Tg between two vertical steps, dark-red represents values higher then the colour-bar.
Every column of the plots come from an IASI map (one every 12h). The black line is the mean altitude of the tropopause computed at the plume pixels.



- Plume is divided in two parts from the beginning (one lower in troposphere and one higher up to tropopause /stratosphere)
- SO_2 near the volcano in every image (continuous emission)
- Nearly one order of magnitude smaller then Nabro (in amount of SO_2) but go to comparable height.



- The highest emission of SO_2 for the period considered (2008-2012).
- Two plumes at different altitudes, the highest one reaches the stratosphere, the lower one remains confined in the troposphere at less then 10 km.
- Fromm et al. (2014): Nabro injected sulphur directly to or above the tropopause upon the initial eruption on 12/13 June, and again on 16 June 2011.

Calbuco – 20 April – 22 May 2015

maximum observed 0.125° re-gridded value for SO2 column loading (DU) and volcanic ash column loading (g/m2)

Vertical distribution of SO2 mass (Tg) over time and Temporal evolution of total mass of SO2 (black squares) & volcanic ash (purple triangles) in regions denoted by black rectangles above.

H_2SO_4 OE - iterative

The forward model is the same as for ash retrieval (Ventress et al 2016) with the difference that we are now using the H2SO4 optical properties.

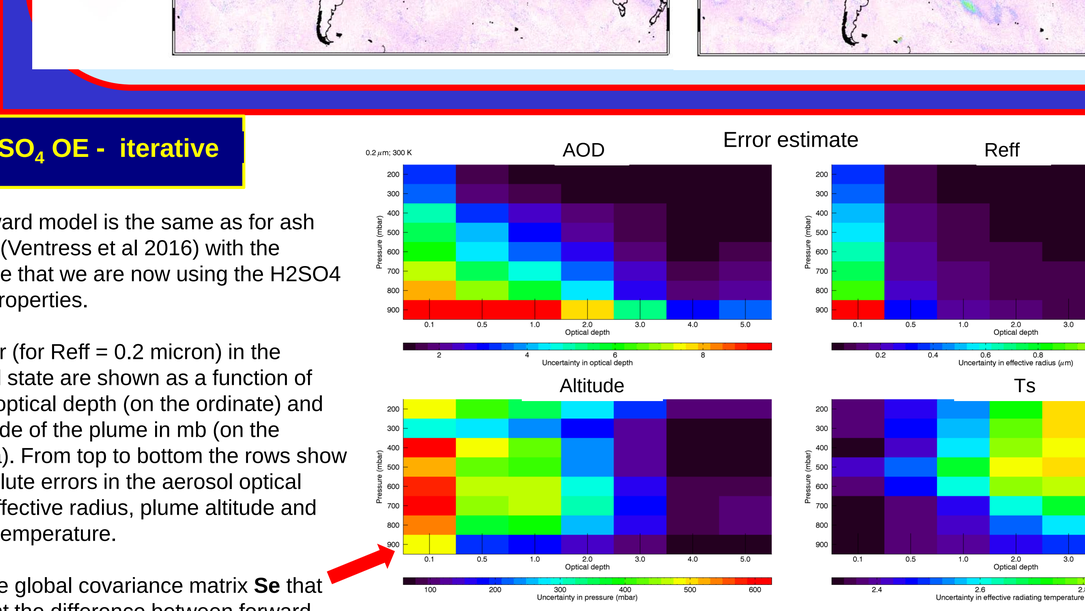
The error (for Reff = 0.2 micron) in the retrieved state are shown as a function of aerosol optical depth (on the ordinate) and the altitude of the plume in mb (on the abscissa). From top to bottom the rows show the absolute errors in the aerosol optical depth, effective radius, plume altitude and surface temperature.

Using the global covariance matrix **Se** that represent the difference between forward model and IASI measurements

$$\mathbf{S}_{\hat{x}} = (\mathbf{K}^T \mathbf{S}_\epsilon^{-1} \mathbf{K} + \mathbf{S}_a^{-1})^{-1}$$

Using only instrumental error to build the covariance matrix Se

First attempt of H_2SO_4 retrieval using the global covariance matrix



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