Vertical distribution of volcanic SO_2 retrieved from IASI.

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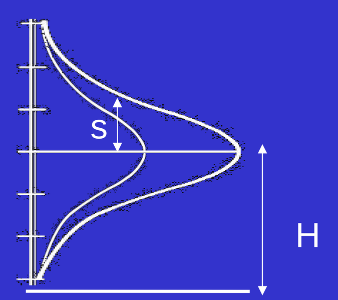
Abstract:

Sulphur dioxide (SO_2) is an important atmospheric constituent that plays a crucial role in many atmospheric processes and its effect and lifetime are dependent on the SO_2 injection altitude. In the troposphere, SO_2 production leads to the acidification of rainfall while in the stratosphere it oxidises to form a stratospheric H_2SO_4 haze that can affect climate for several years.
We report applications of IASI high resolution infrared spectra to study volcanic emission of sulphur dioxide (SO_2). IASI is a Fourier transform spectrometer that covers the spectral range 645 to 2760 cm^{-1} (3.62-15.5 µm). The IASI field of view consists of four circles of 12 km inside a square of 50 x 50 km, and nominally it can achieve global coverage in 12 hours. From 2013 there were two IASI instruments on board both METOP A and B giving up to four overpasses a day.
The SO_2 retrieval algorithm uses measurements from 1000 to 1200 cm^{-1} and from 1300 to 1410 cm^{-1} (the 7.3 and 8.7 µm SO_2 bands) made by IASI on the MetOp satellite. The SO_2 retrieval follows the method of Carboni et al. (2012) and retrieves SO_2 amount and altitude together with a pixel-by-pixel comprehensive error budget analysis. It permits the quantification of SO_2 amount and estimation of plume altitude, even for small eruptions in the lower troposphere (e.g. Etna lava fountains in 2011 and 2013).
We present the SO_2 amount described as a function of altitude, and the time evolution of SO_2 burden for recent volcanic eruptions. Quantification of the total amount of SO_2 over several days allows estimation of daily emission rates, and decay factors.

Retrieval scheme

The SO_2 retrieval algorithm uses measurements from 1000 to 1200 cm^{-1} and from 1300 to 1410 cm^{-1} (the 7.3 and 8.7 µm SO2 bands) made by IASI (Carboni et al., 2012).
This retrieval scheme determines the column amount and effective altitude of the SO_2 plume with high precision (up to 0.3 DU error in SO_2 amount if the plume is near the tropopause) and can retrieve informations in the lower troposphere.

There are several advantages of the IASI retrievals:
(1) IASI makes measurements both day and night (so has **global coverage every 12 hours**),
(2) the IASI retrieval does not assume plume height but **retrieves an altitude for maximum SO_2 amount** (under the assumption that the vertical concentration of SO_2 follows a Gaussian distribution).
(3) IASI retrievals is **not affected by underlying cloud** (if the SO_2 is within or below an ash or cloud layer its signal will be masked and the retrieval will underestimate the SO_2 amount, in the case of ash this is a posteriori discernible by the cost function value)
(4) A **comprehensive error budget for every pixel** is included in the retrieval. This is derived from an error covariance matrix that is based on the SO_2-free climatology of the differences between the IASI and forward modelled spectra.



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

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

F(x)

Forward model: fast radiative transfer (RTTOV + SO_2 RAL coefficients)

IASI simulated spectra

IASI measurements → OE retrieval

$$J = (\mathbf{y} - F(\mathbf{x}) - \mathbf{b})^T \mathbf{S}_e^{-1} (\mathbf{y} - F(\mathbf{x}) - \mathbf{b}) + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

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

best estimate of stare vector:
SO_2 amount, plume altitude, Ts

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

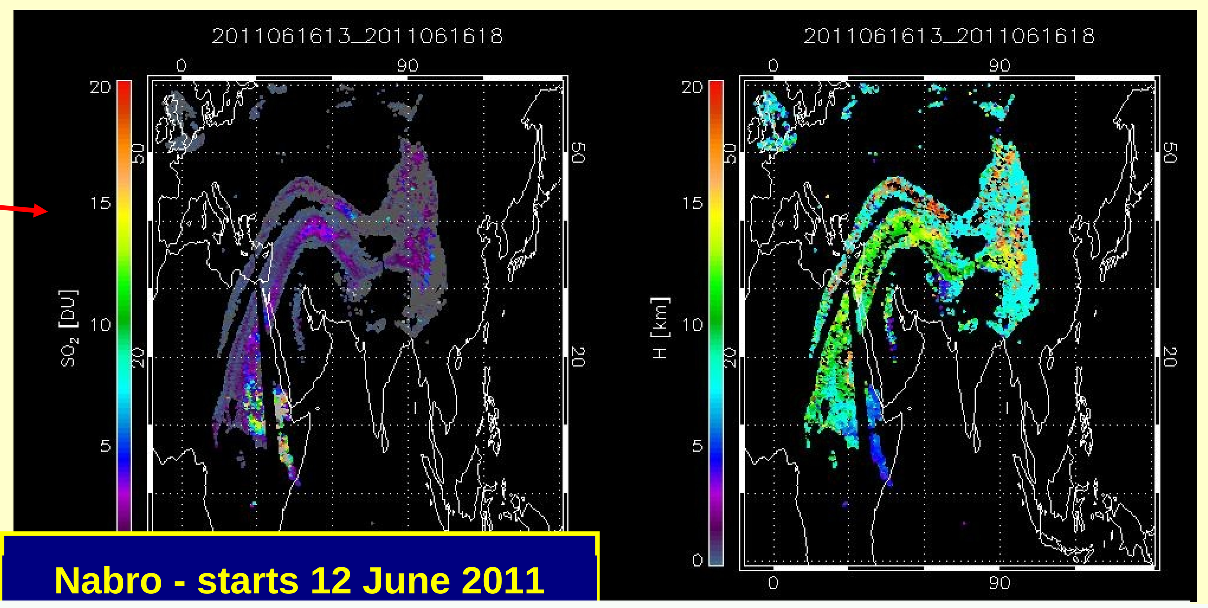
$$y_s = F(SO_2=0)$$

Sy Computed with billions pixels

Note that the measurement covariance, $\mathbf{S_y}$, is defined to represent the effects of atmospheric variability not represented in the forward model (FM), as well as instrument noise. This includes the effects of cloud and trace-gases which are not explicitly modelled. 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 SO_2 are present.

Volcanic eruptions

Every ~12 hours we produce maps of IASI retrieved SO_2 amount and altitude
Example here

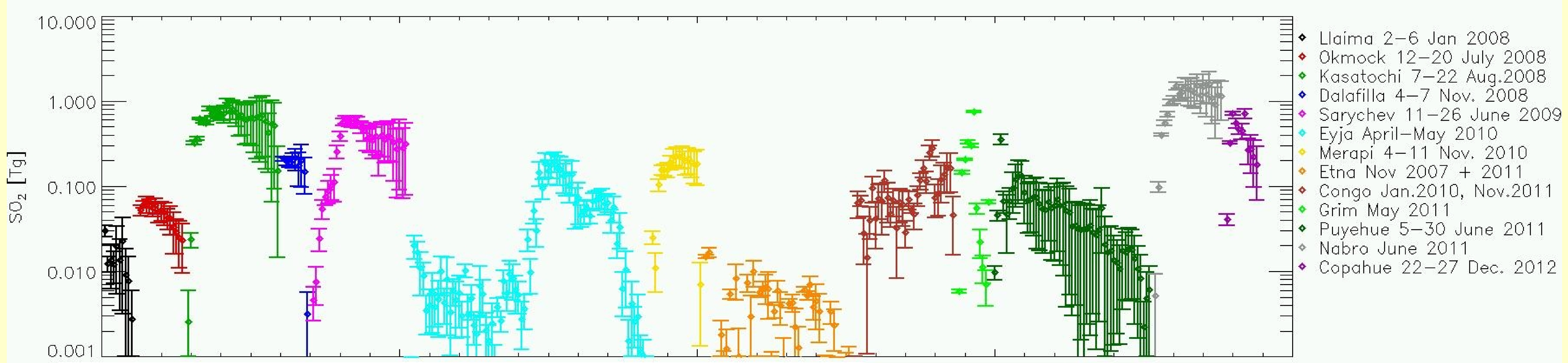


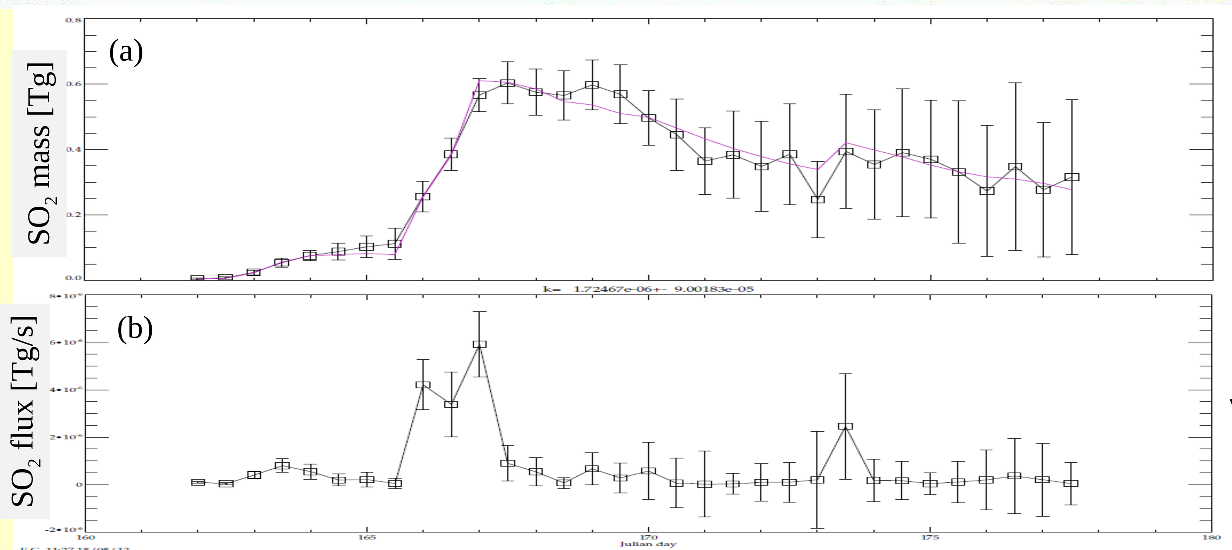
Nabro - starts 12 June 2011

The total SO_2 mass present in the atmosphere is obtained summing all the values of a regularly gridded map of SO_2 amounts.
In this way the main volcanic eruptions are summarized in the plots below.

Nabro produces the largest amount of SO_2 plume observed by IASI with a maximum of up to ~2 Tg of SO_2.

SO_2 retrieved from IASI data. The values are the measured amount on a particular day and vary with volcanic emission, gas removal and satellite sampling. Points are separated by ~12 hours.





For any eruption we have a time series of the total mass of SO_2 present in atmosphere and its associated uncertainty.
We use this SO_2 mass as 'measurements' in a OE retrieval to estimate a state vector composed of: the exponential factor k and the average flux f_i (every 12h).

$$x=(k,f_1,f_2,f_3,f_4,\ldots)$$

The forward model considered is:

$$y_i = f_i \, \Delta t + y_{(i-1)} \exp(-k \, \Delta t)$$

The factor k includes all processes that influence the decrease in SO_2 mass such as as depletion, dilution and dissipation. This is largely unconstrained and the retrieved error is about 50%.

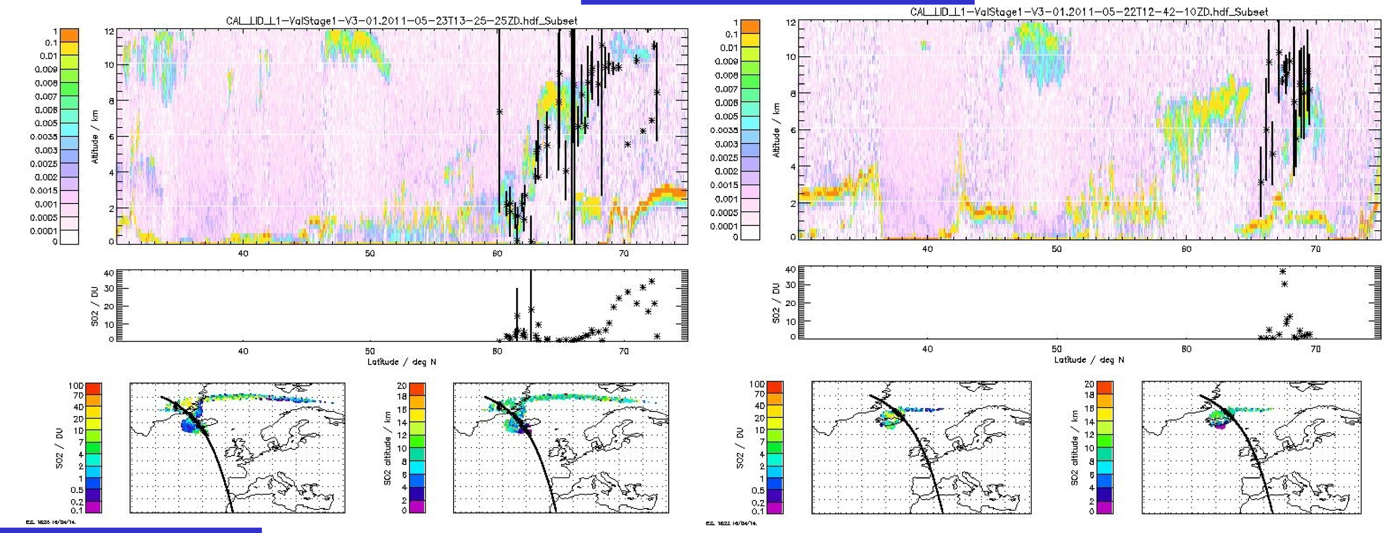
Example for the Sarychev eruption: (a) the total mass as a function of time in black (with error bars) and the that simulated by the forward model at the end of the retrieval iteration in purple; (b) the retrieved SO_2 fluxes with error bars.

Height validation

Comparison with CALIPSO.:
The CALIPSO data are preselected with SEVIRI to identify the location of volcanic plume (G. Thomas, personal communication).

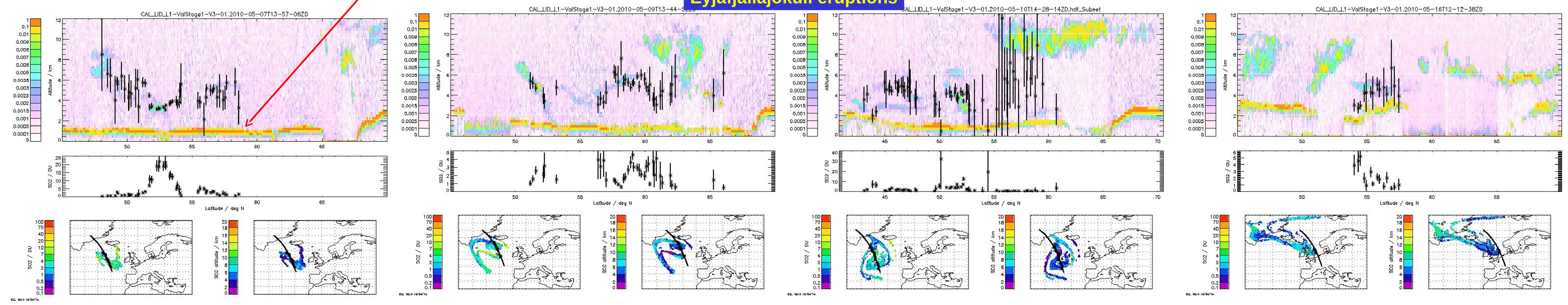
Here the height of the SO_2 plume from the IASI pixel closest to CALIPSO track, are overplotted on the CALIPSO backscattering profile.
Coincidence criteria are < 100 km distance and <2 hours difference in time between the two measurements. With this relatively 'strict' criteria only the two Icelandic eruptions (reported here) have some coincidences (ideal coincidence between Metop-A and A-train is at ~70 deg. lat.). A greater time difference allows comparisons with more eruptions, but the quality of the comparison will decrease and the plume evolution may be needed to be considered.
Note that CALIPSO's backscatter signal comes from ash and/or H_2SO_4 droplets (mostly from the oxidation of SO_2).

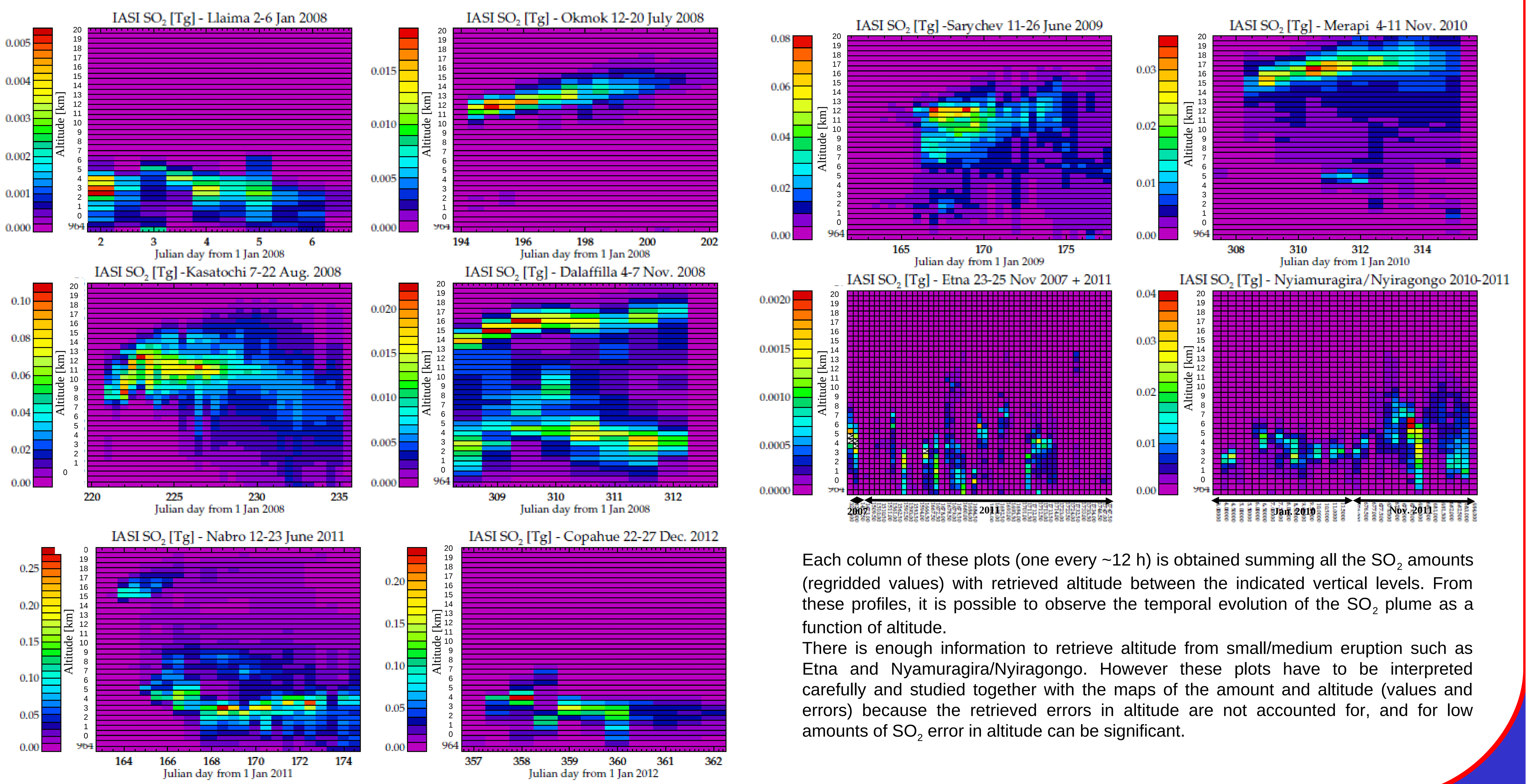
Grímsvötn eruption



Note that underlying cloud doesn't affect the retrieval

Eyjafjallajökull eruptions





Each column of these plots (one every ~12 h) is obtained summing all the SO_2 amounts (regridded values) with retrieved altitude between the indicated vertical levels. From these profiles, it is possible to observe the temporal evolution of the SO_2 plume as a function of altitude.
There is enough information to retrieve altitude from small/medium eruption such as Etna and Nyamuragira/Nyiragongo. However these plots have to be interpreted carefully and studied together with the maps of the amount and altitude (values and errors) because the retrieved errors in altitude are not accounted for, and for low amounts of SO_2 error in altitude can be significant.

Summary

-IASI SO_2 scheme retrieves the height and amount of SO_2 and provides a comprehensive error budget for every pixel.
-Uses the detection scheme (Walker et al. 2012) applied to pixels for the full retrieval (Carboni et al 2012). See poster B273 for the NRT development of this linear retrieval.
-Retrieved uncertainties increase with the decreasing of altitude, and the decreasing of the amount, nevertheless it is possible to retrieve information in the lower troposphere and monitor volcanic degassing.
-Underlying cloud don't affect the retrieval, cloud at the same altitude or above the plume mask the SO_2 signal. (see Carboni et all 2012)
-New developments towards the ash retrieval is reported in Ventress talk (today, room G8 at 14:30)
-Comparison and validation within the SMASH-SACS2 projects are presented in posters B286, B288 (today) and B790 (on Friday)

Retrieval scheme and Eyjafjallajökull eruption :
Carboni, E., Grainger, R., Walker, J., Dudhia, A., and Siddans, R.: A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010, Atmos. Chem. Phys., 12, 11417-11434, doi:10.5194/acp-12-11417-2012, 2012.

Detection scheme:
Walker, J.C., E. Carboni, A. Dudhia, R.G. Grainger: Improved Detection of Sulphur Dioxide in Volcanic Plumes using Satellite-based Hyperspectral Infra-red Measurements: Application to the Eyjafjallajokull 2010 Eruption, J. Geophys. Res., 117, doi:10.1029/2011JD016810, 2012.

ACKNOWLEDGMENTS

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