Volcanic sulphur dioxide (SO_2) in atmosphere from IASI data: analysis of SO_2 amount and altitude for recent eruptions and volcanic degassing.

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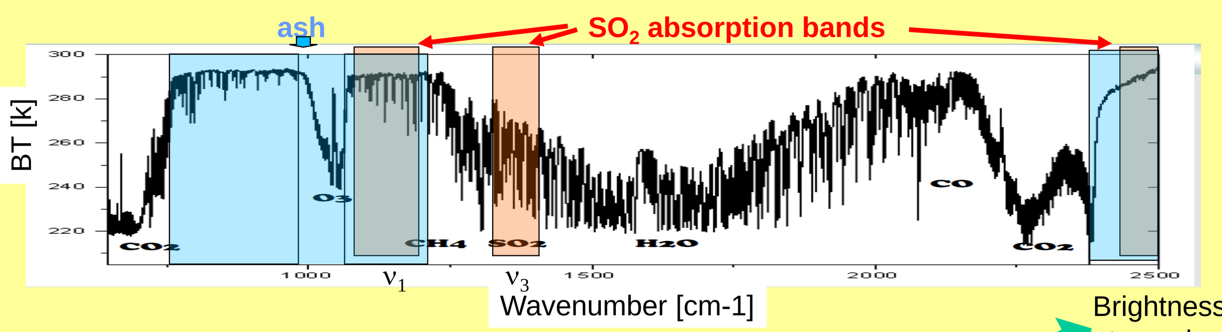
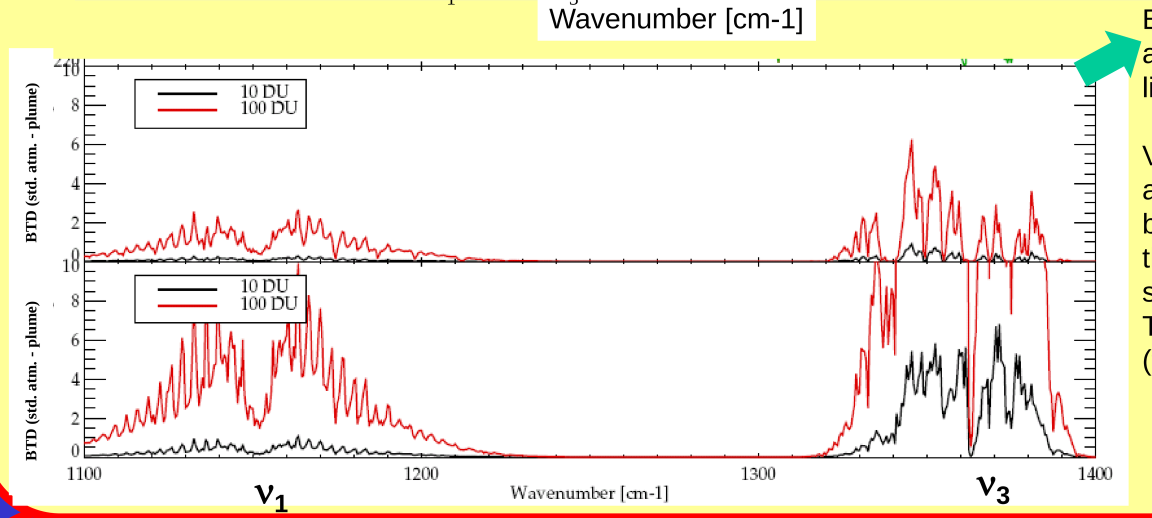
Infrared Atmospheric Sounding Interferometer - IASI



IASI is on board of METeorological OPerational satellite program (METOP), an European meteorological satellite that is operational from 2007. METOP-A is the first of three polar satellites that will span the next fourteen years. It crosses the equator at the local time of 9.30 am. IASI is a Fourier transform spectrometer, that measures the spectral range 645 to 2760 cm^{-1} (3.62−15.5μm) with a spectral sampling of 0.25 cm^{-1} and a apodised spectral resolution of 0.5 cm^{-1}. Radiometric accuracy 0.25-0.58K. The IASI field of view (FOV) consists of four circles of 12 km diameter (at nadir) inside a square of 50 x 50 km, step-scanned across track (30 steps). It has a 2000 km swath and nominally can achieved the global coverage in 12 hours (although there are some gaps between orbits at the equatorial tropical latitudes). Radiances are collocated with the Advanced Very High Resolution Radiometer (AVHRR) that can be potentially useful, with complementary visible/near infrared channel, for cloud and aerosol retrieval.



Brightness temperature differences (BTD) between the the reference clear atmosphere and the reference clear atmosphere with enhanced tropospheric/stratospheric (top/bottom) SO_2 containing a total column amount of 10DU (black line) or 100DU (red line) of SO_2;

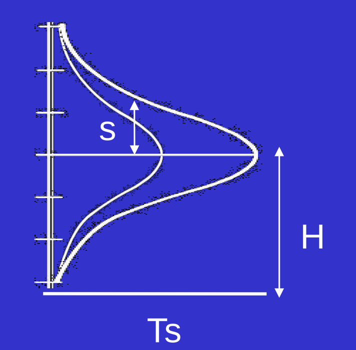
Volcanic SO_2 retrievals from satellite data in the thermal infrared spectrum are based on two regions of SO_2 absorption around 7.3 (ν3) and 8.7 (ν1) μm. The strongest SO_2 band is at 7.3 μm, within a strong water vapour (H_2O) absorption band. Observations in this range are therefore not very sensitive to emission from the surface and lower atmosphere, but this band contains valuable information on the vertical profile of SO_2. Differences between the H_2O and SO_2 emission spectra allow the signals from the two gases to be decoupled in high resolution measurements.
The 8.7 μm absorption feature is in an atmospheric window so it contains information on SO_2 from throughout the column (though limited by .the reducing temperature contrast towards the surface and cloud).

- IASI is sensitive to both the amount of SO_2 and the altitude of the plume
=> getting the altitude correct is important in order to get the correct *amount* of SO_2, since the signal depends strongly on altitude.

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 m 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 modeled. 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.

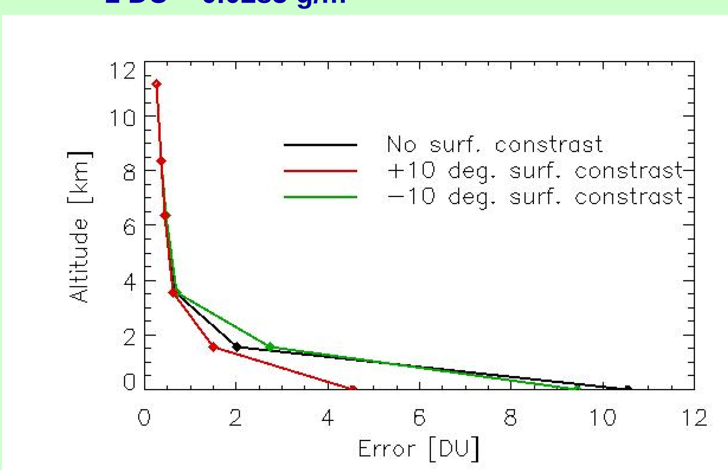
Minimum error estimate

surface contrast = skin temperature - temperature of the first atm. layer

std. atm. profiles
assumption: we know the altitude of the plume.

1 DU = 0.0285 g/m^2

considering 60 overpasses/ month
=> error reduced of 1/sqrt(60)

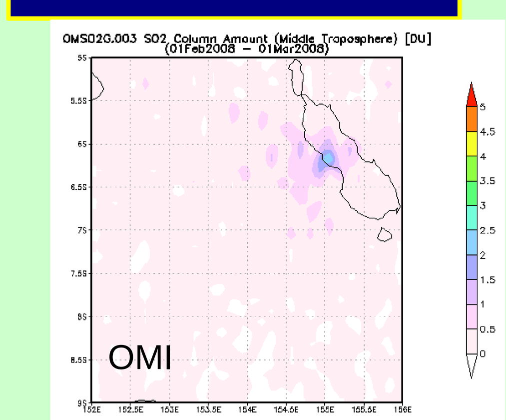


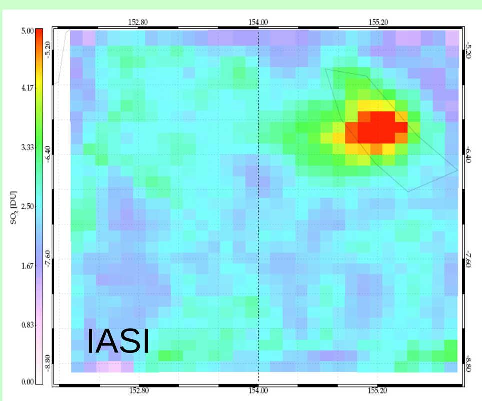
SO_2 monthly errors

[km]	[g/m2]
11	$9\ 10^{-4}$
8.3	$13\ 10^{-4}$
6.4	$17\ 10^{-4}$
3.5	$24\ 10^{-4}$
1.5	$73\ 10^{-4}$
0	$388\ 10^{-4}$

Bagana - February 2008

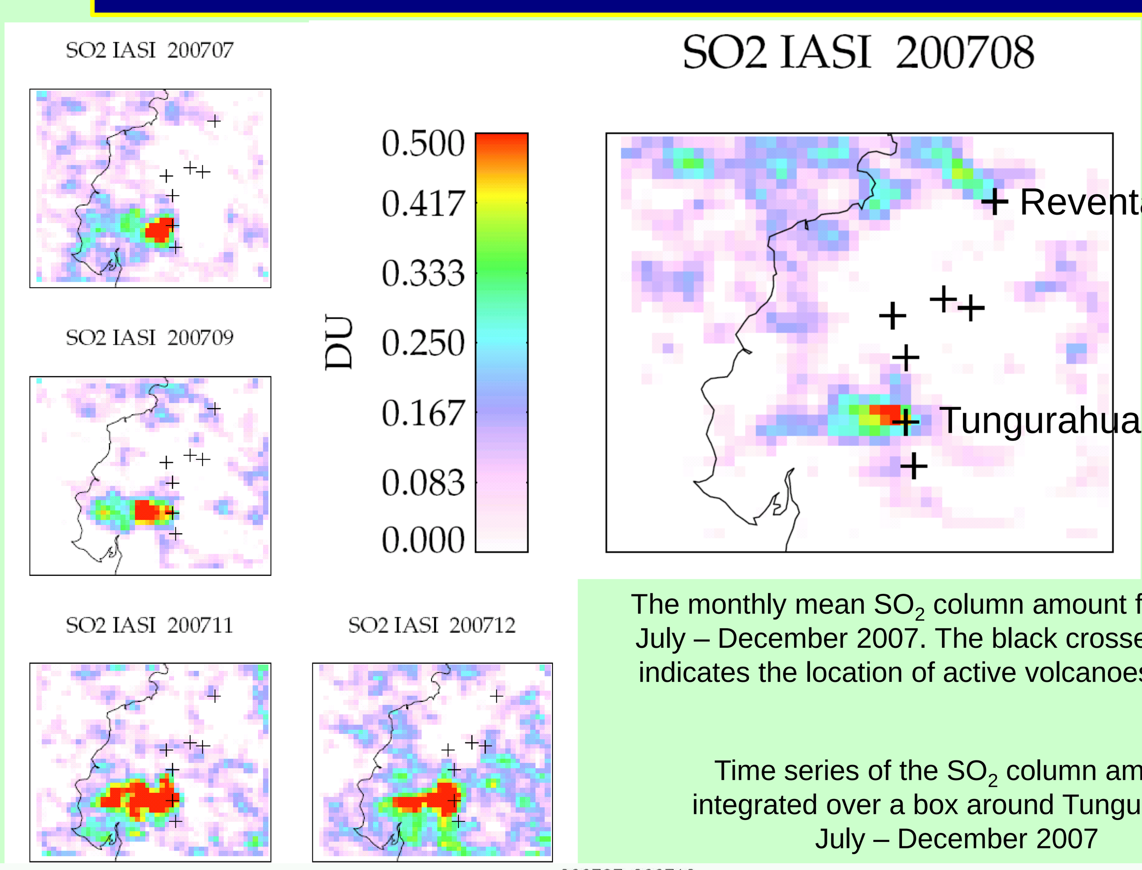
IASI detect between 2 and 4 time more SO_2 then OMI for Bagana degassing on Feb. 2008





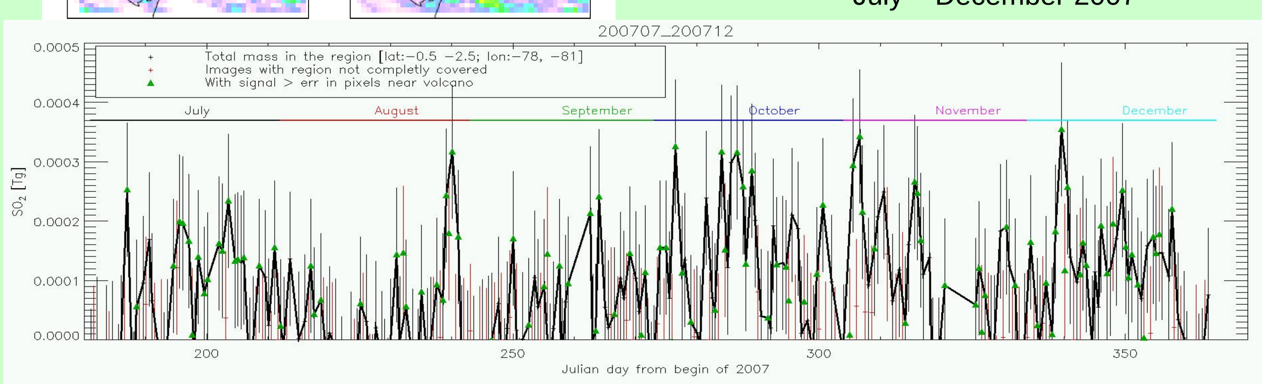
OMI monthly mean is produced with the Giovanni online data system, developed and maintained by the NASA GES DISC: http://gdata2.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=omil2g

Ecuador monthly mean - degassing



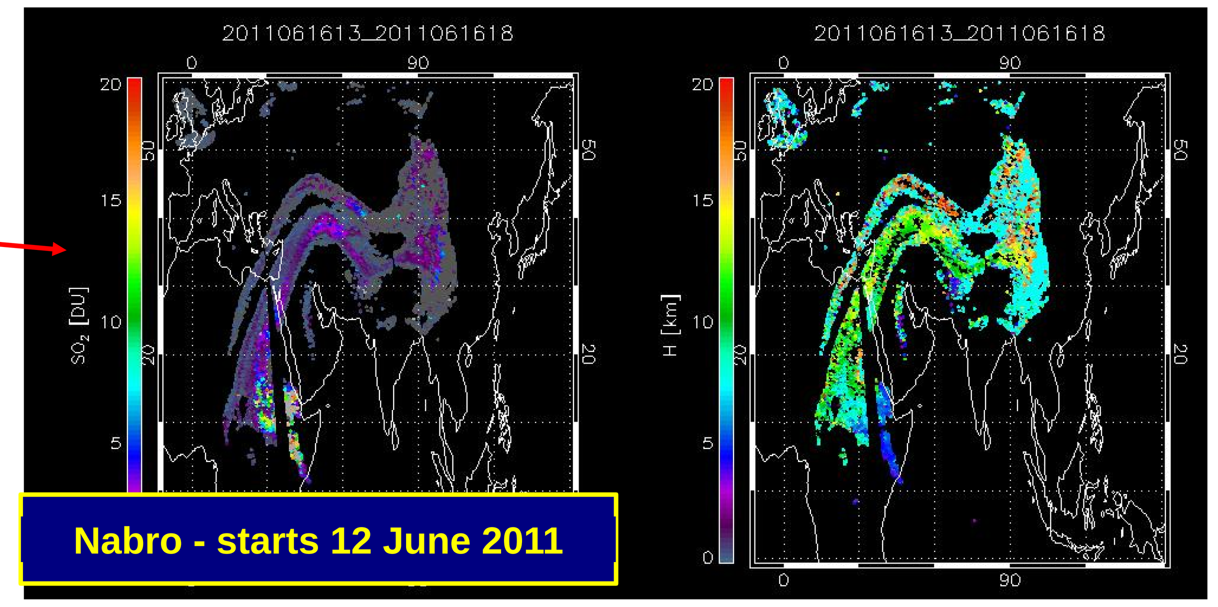
The monthly mean SO_2 column amount for July – December 2007. The black crosses indicates the location of active volcanoes.

Time series of the SO_2 column amount integrated over a box around Tungurahua. July – December 2007



Volcanic eruptions

Every ~12 hours it is possible to have maps of IASI retrieved SO_2 amount and altitude Example here

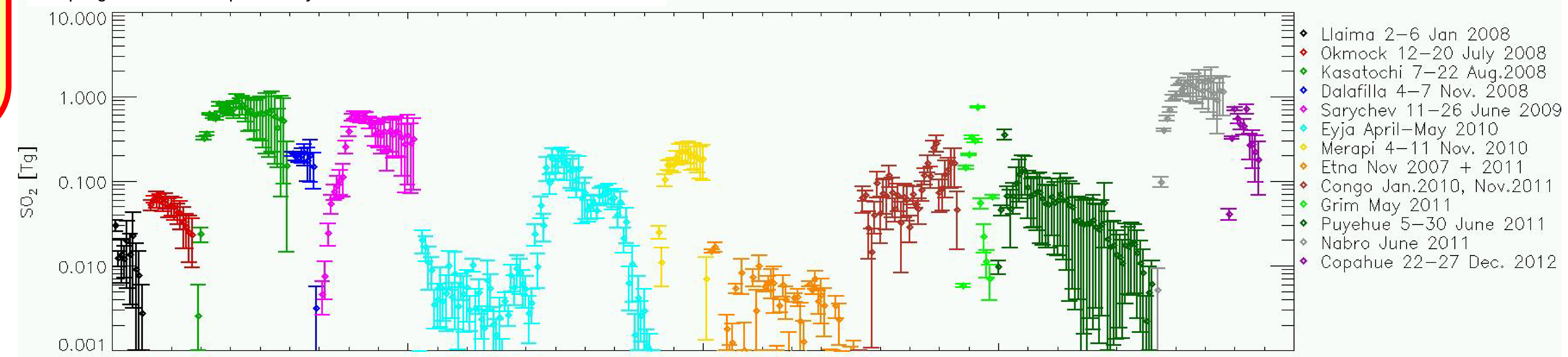


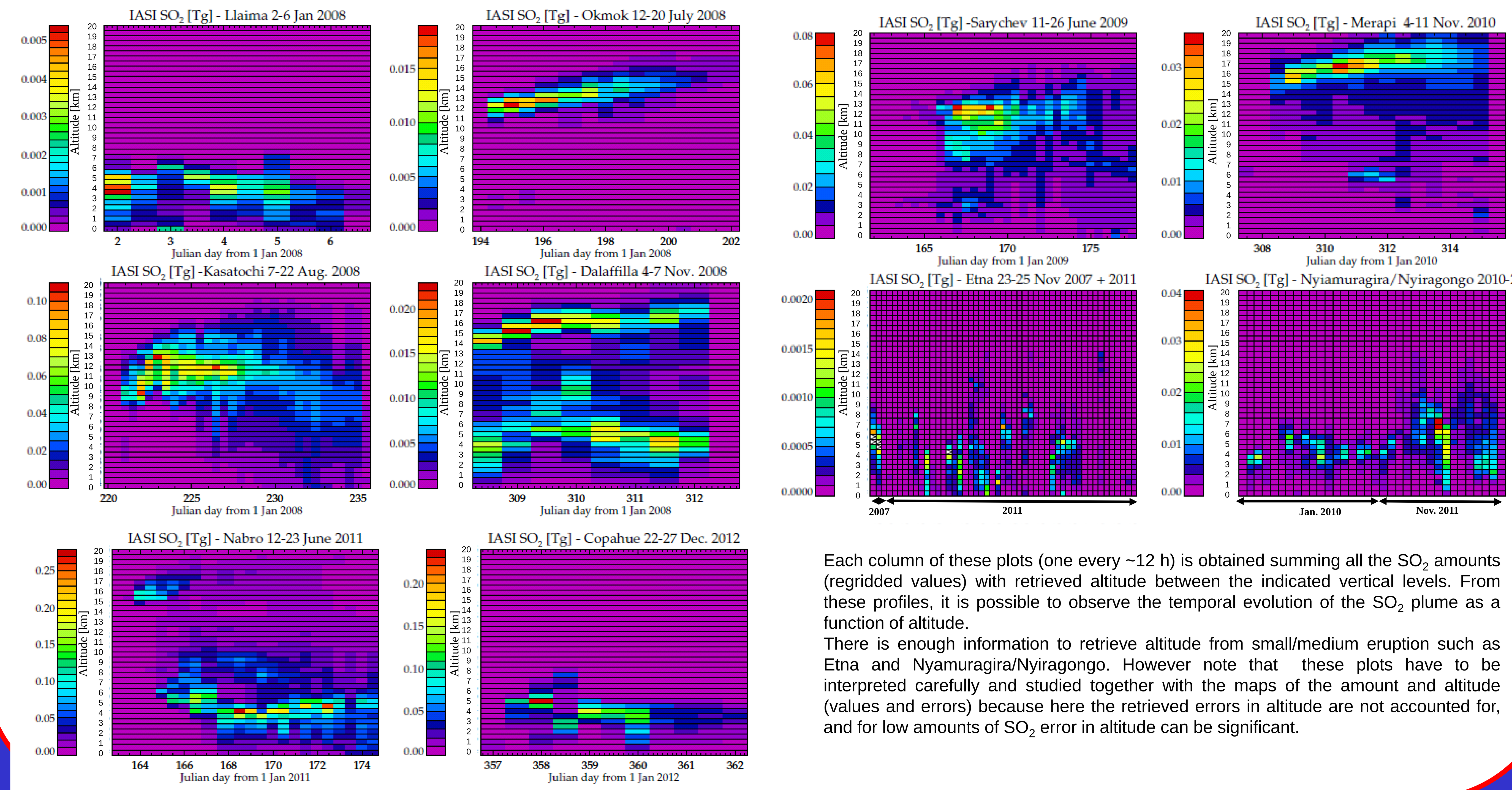
Nabro - starts 12 June 2011

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.





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 note that these plots have to be interpreted carefully and studied together with the maps of the amount and altitude (values and errors) because here 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).
- Retrieved uncertainties increase with the decreasing of altitude, nevertheless it is possible to retrieve information in the lower troposphere and monitor volcanic degassing.
- Thick ash can affect the retrieval, recognizable from cost >2 (see Carboni et all 2012)
- 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)
- Comparison with other satellite retrievals is reported in the Corradini talk; Thursday at 14:45, Room G6
- New developments towards a consistent retrieval of SO_2 and ash is reported in another poster (Thursday, blue posters, B252)

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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