Sulphur dioxide retrieval from satellite measurements (IASI): a new optimal estimation retrieval scheme and results for recent volcanic eruptions.

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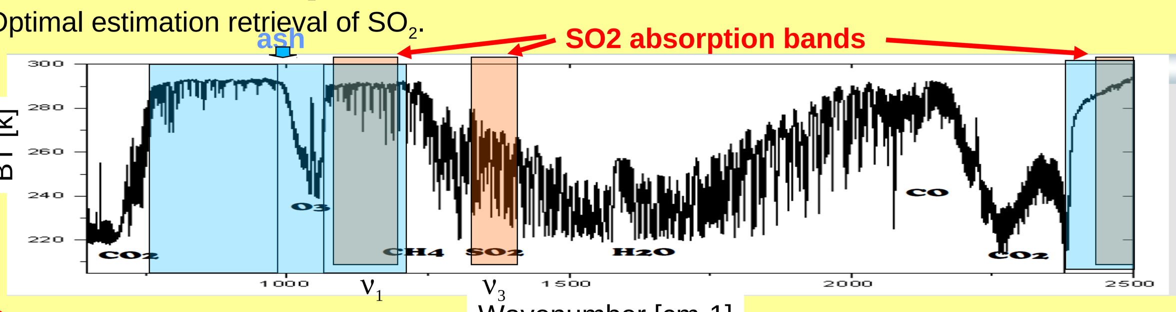
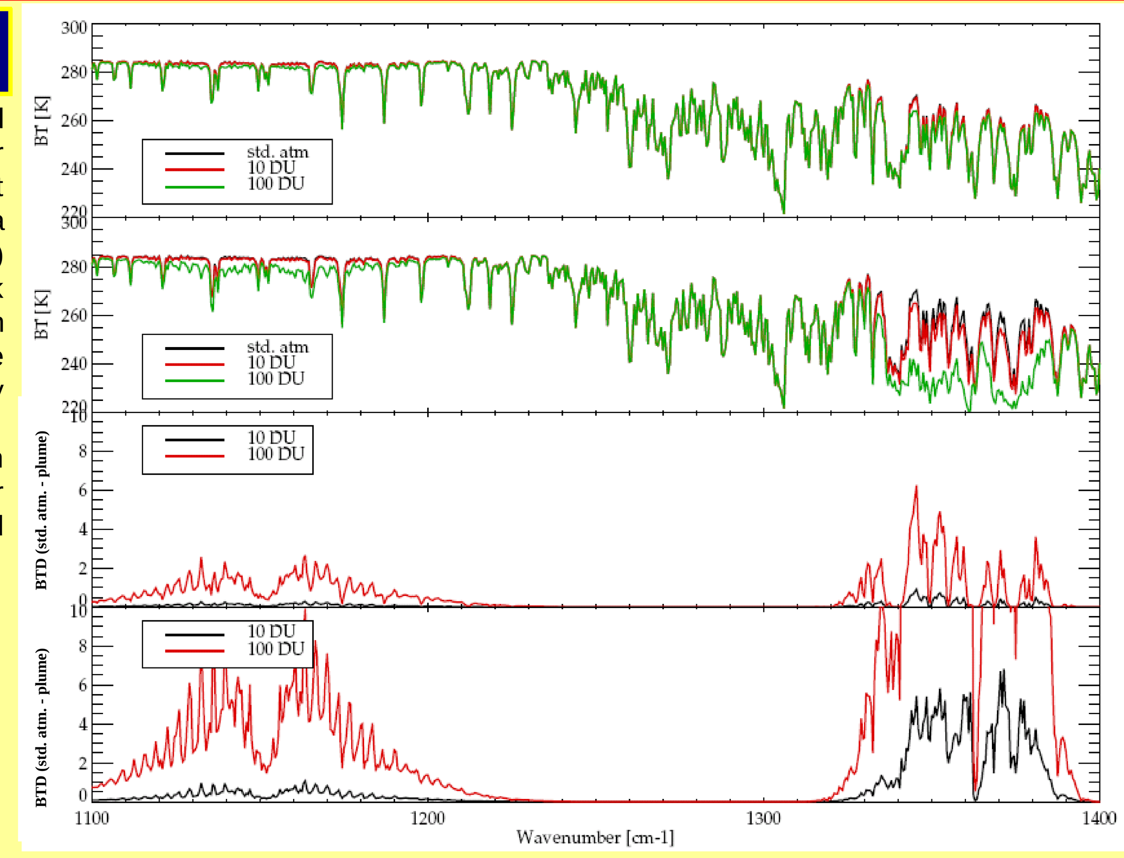
ABSTRACT:
A new algorithm for the retrieval of sulphur dioxide from IASI data has been developed based on optimal estimation theory [Rodger 2000]. It uses the IASI channels between 1000-1200 and 1300-1410 cm-1. These regions include the two SO_2 absorption band features (the v1 and v3 absorption bands) centred at about 7.3 and 8.7 microns respectively. The retrieval assumes a Gaussian distribution for the vertical SO_2 profile and returns the SO_2 column amount [in Dobson units] and the altitude of the plume [in mb].
Radiative transfer computations that generate the forward modelled spectra (against which the measurements are compared) are based on RTTOV (Saunders et al.,1999) and ECMWF meteorological data.
The retrieval includes a comprehensive error budget for every pixel. This is derived from an error covariance matrix that is based on the SO2-free climatology of the differences between the IASI and forward modelled spectra.
The IASI forward model includes the possibility to simulate a cloud or ash layer in the atmosphere, this feature is used to illustrate that: (1) the SO_2 retrieval is not affected by underling cloud but is effected if the SO_2 is within or below a cloud layer; (2) it is possible to discern if ash (or other atmospheric constituents not considered in the error covariance matrix) affect the retrieval using quality control based on the fit of the measured spectrum by the forward modelled spectrum. In this work we present the algorithm and some results for recent volcanic eruptions.

Infrared Atmospheric Sounding Interferometer - IASI

IASI in on board of METeorological OPerational satellite program (METOP), an European meteorological satellite that is operational from 2007. METOP is the first of tree polar satellite system (EPS) that will cover fourteen years. It cross the equator at the local time of 9.30 am. IASI is a fourier transform spectrometer, that cover 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) consist of of four circle of 20 km diameter (at nadir) inside a square of 50 x 50 km, step-scanned across track (30 steps). It have 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. IASI make nadir observation of the earth simultaneously with Global Ozone Monitoring Experiment (GOME-2) also on board of METOP. GOME-2 is an UV spectrometer that contain also the SO_2 signature in the UV absorption band and have been used for both DOAS and Optimal estimation retrieval of SO_2.





The 7.3 µm feature (ν_3) is the strongest, it is inside a strong water vapour absorption band and so:
(1) it is not very sensitive to surface and the lower atmospheric layer;
(2) the different spectral shapes of the water vapour and SO_2 absorption features provide valuable information on the vertical profile of SO_2.

The 8.7 µm absorption feature (ν_1) contains SO_2 information also in the case of lower tropospheric plumes. It is in an atmospheric window (relatively high transmittance to the surface), but by itself does not contain significant spectral information about the plume altitude or plume profile. Nevertheless, it is probably the most useful region for monitoring those volcanoes characterized by continuous quiescent degassing.

- IASI is sensitive to both the amount of SO2 and the altitude of the plume, amount and altitude have different spectral signature => we attempt to retrieve both

- Note that getting the altitude correct is important not just for itself, but also in order to get the correct *amount* of SO2, since the signal depends strongly on altitude.

OPTIMAL ESTIMATION APPROACH

$$J=(y-F(x))^T S_y^{-1}(y-F(x))+(x-x_a)^T S_a^{-1}(x-x_a)$$ (Rodgers 2000)

y is the measurement vector, *x* the state vector, *F* forward model → physics, radiative transfer; S_y measurement error vector

Usually:
y would contain the IASI measured radiances
S_y would represent noise on those measurements
x would contain all atmospheric + surface parameters that affect these radiances and are imperfectly known - in this case including H_2O,T, cloud and many other minor species, as well as SO_2.

However: - We're not interested in most of these potential state variables
- SO_2 is very rarely present in significant amounts in the IASI spectra (except during volcanic eruptions and degassing regions)
- H_2O,T are well predicted by Met data
- Other gases have features which are spectrally uncorrelated with SO_2

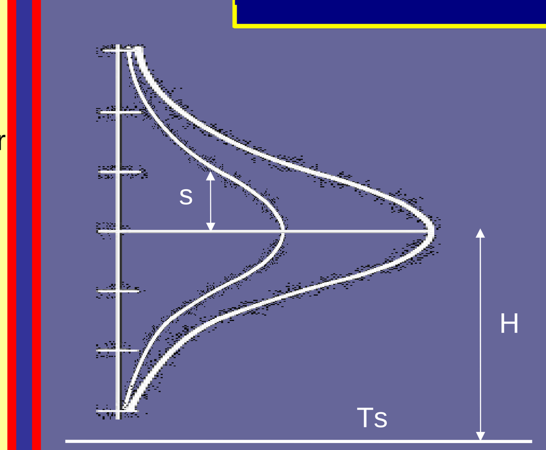
We can greatly simplify the retrieval problem by including in the S_y covariance matrix all the differences between the IASI observed radiances and radiances predicted by a forward model, based on ECMWF met data.

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

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

We compute the error covariance S_y using similar conditions but when we know there is no SO_2 in the atmosphere.
This will give a measurement covariance which allows deviations due to cloud and other trace-gases but still enables the SO_2 signature to be detected.
For Eyja eruption we consider the data, in the same geographic region, of the same month the year before (eg. April or May 2009). We also use a global covariance matrix, considering all the data of 4 days (1 every season) of 2009 (4 day - 14 orbit a day-> 5x10^6 pixels)

Fast forward model



State vector:
- Total column amount of So2
- Altitude H
- ~~Thickness~~ s
- Surface temperature Ts

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

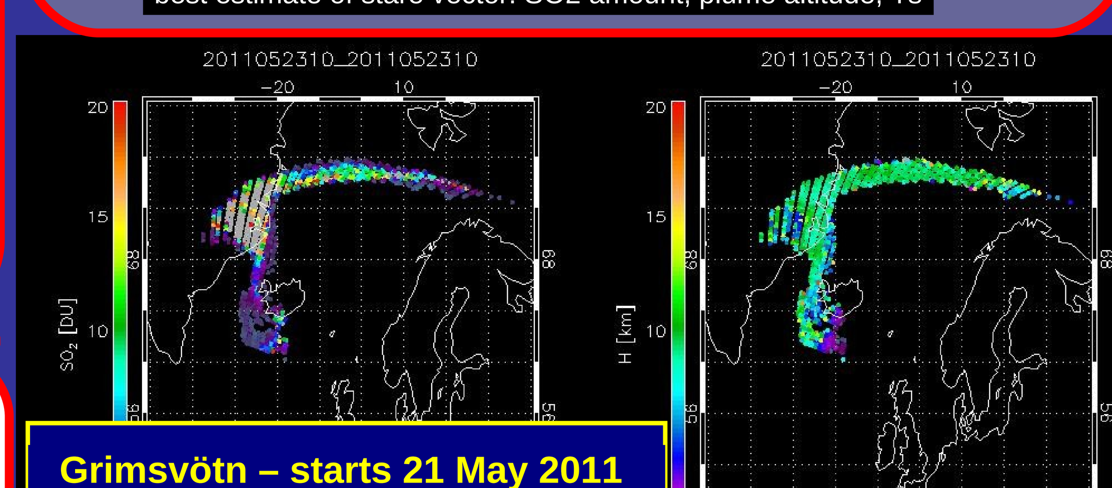
FM: fast radiative transfer (RTTOV + SO2 RAL coefficients)

IASI simulated spectra

IASI measurements

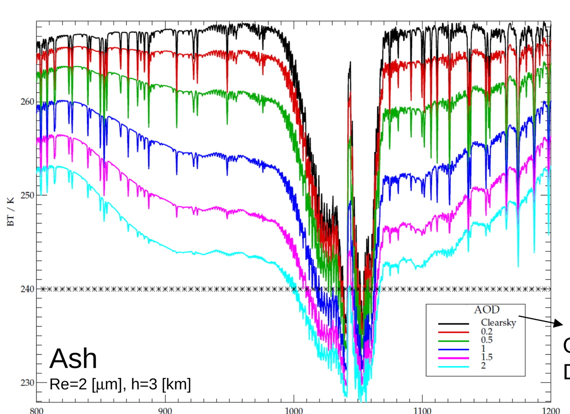
OE retrieval

best estimate of stare vector: SO2 amount, plume altitude, Ts



Grimsvötn – starts 21 May 2011

Ash and cloud effects?



To test if the retrieval is sensitive to ash/cloud etc...

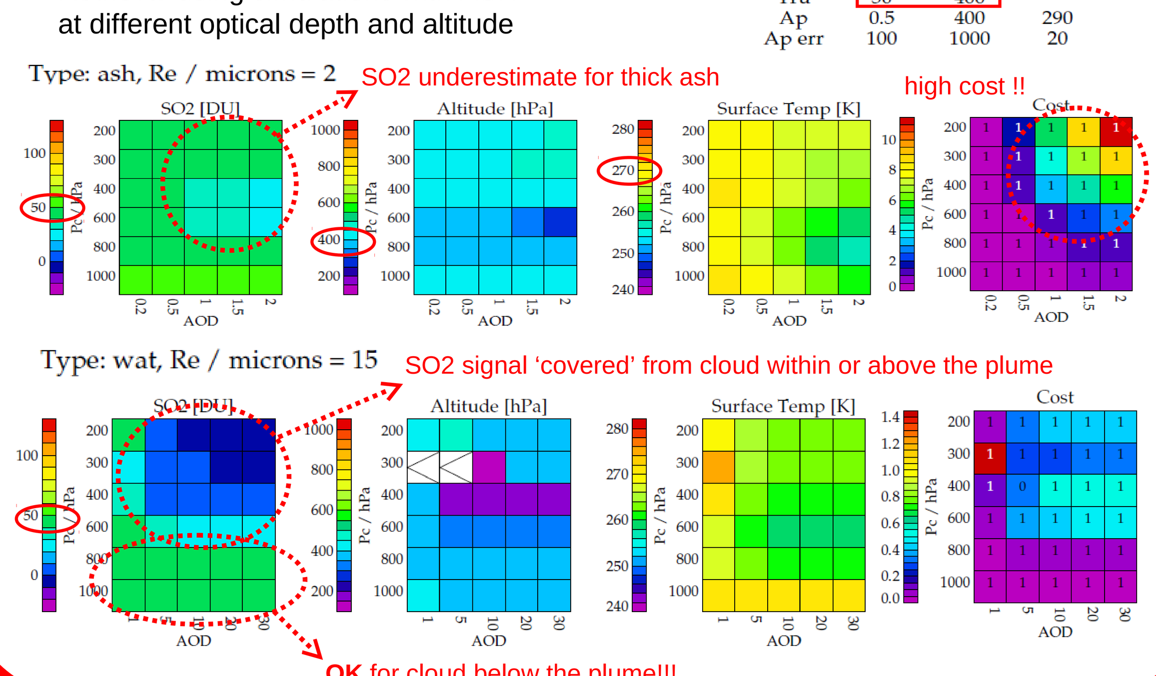
IASI forward model can include aerosol and cloud.

Obtained with refractive index measured by Daniel Peters.

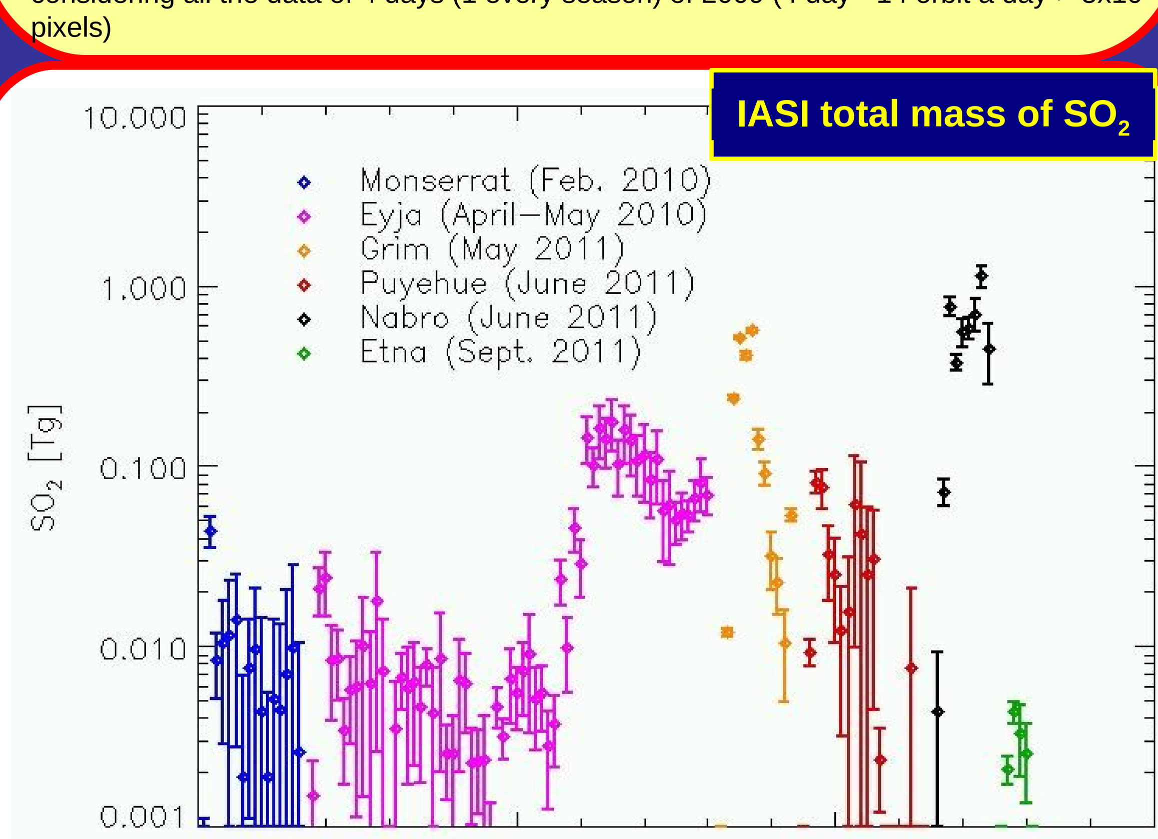
Sensitivity of retrieval to presence of ash and cloud

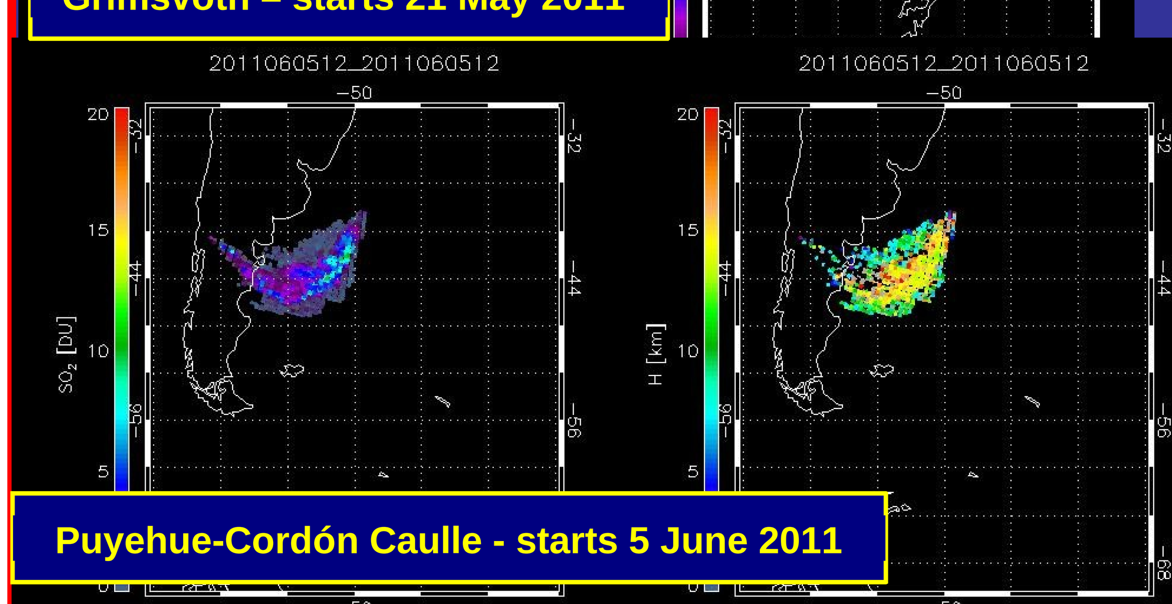
Retrieval using simulations with ASH at different optical depth and altitude

	DU	hPa	T [K]
Tru	50	400	
Ap	0.5	400	290
Ap err	100	1000	20

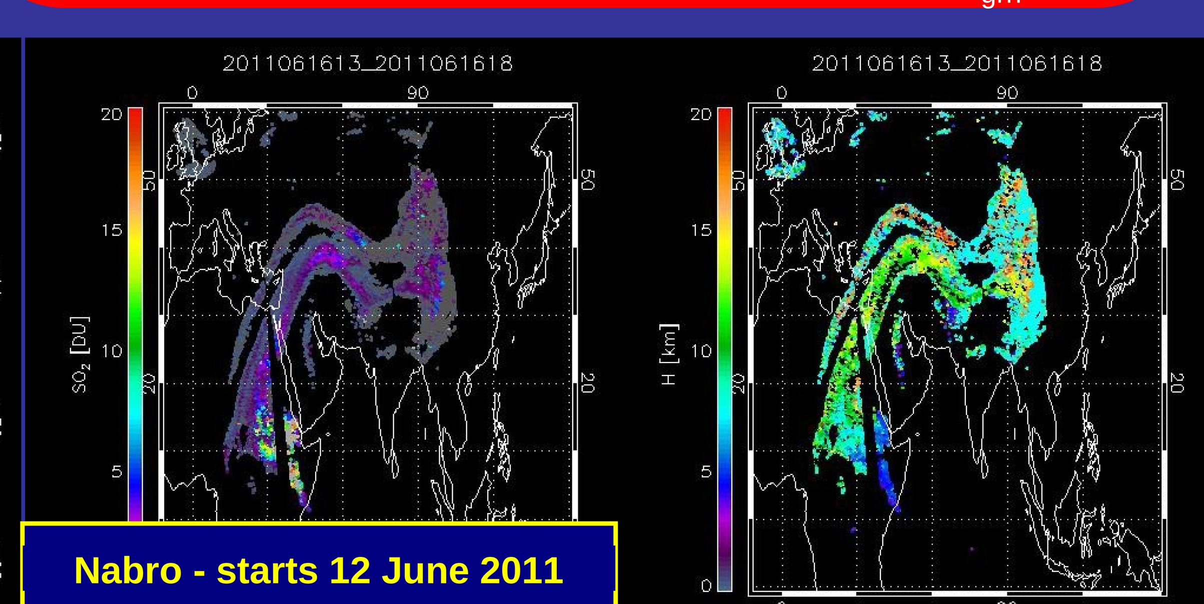


IASI total mass of SO_2





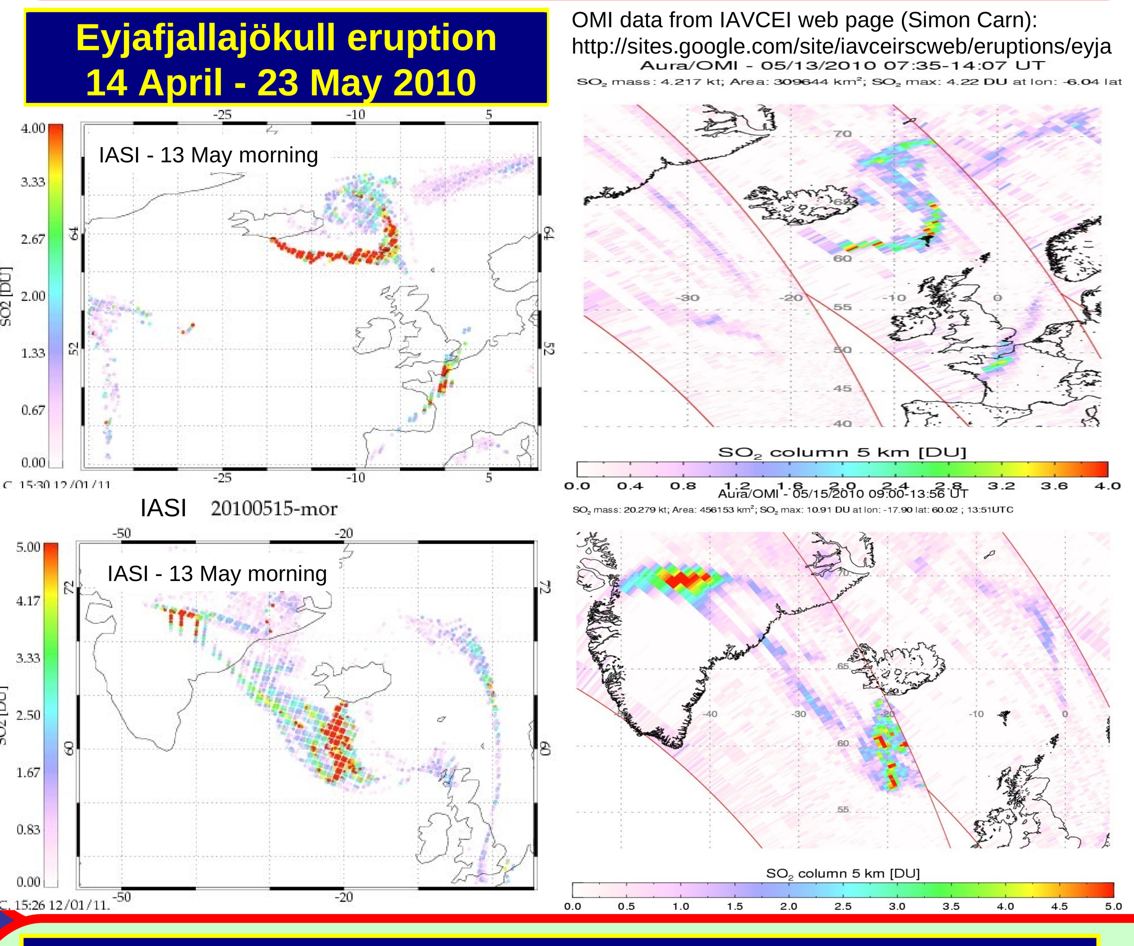
Puyehue-Cordón Caulle - starts 5 June 2011

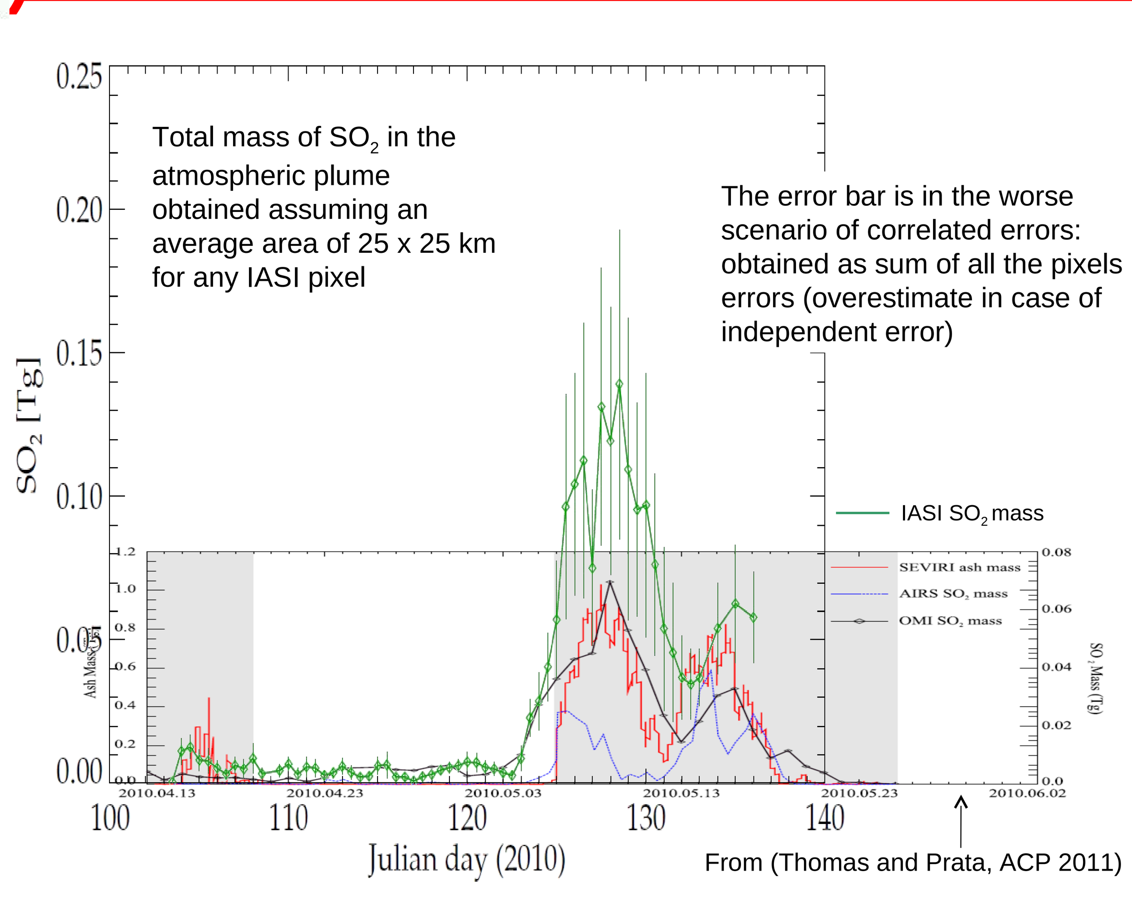


Nabro - starts 12 June 2011

Eyjafjallajökull eruption 14 April - 23 May 2010

OMI data from IAVCEI web page (Simon Carn): http://sites.google.com/site/iavceirscweb/eruptions/eyja



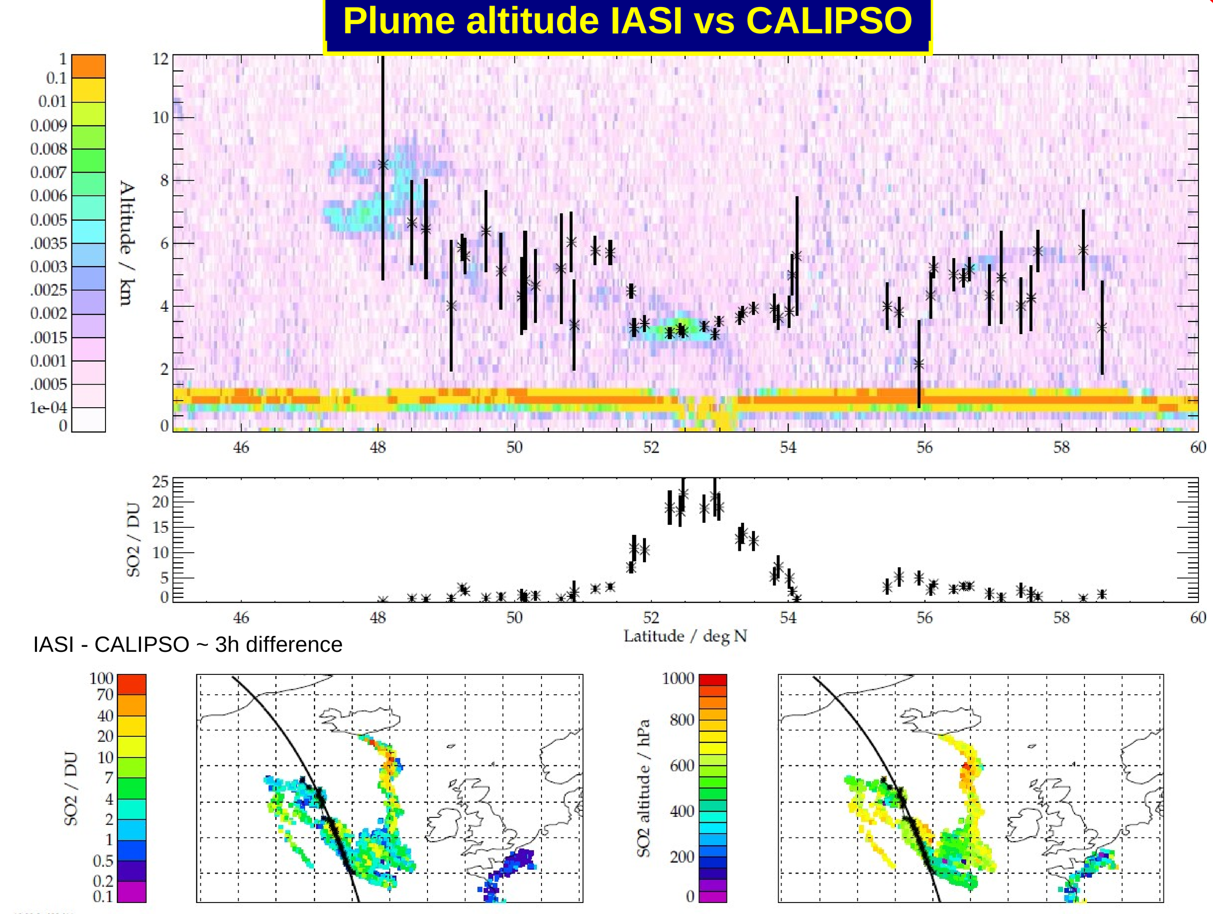


Total mass of SO_2 in the atmospheric plume obtained assuming an average area of 25 x 25 km for any IASI pixel

The error bar is in the worse scenario of correlated errors: obtained as sum of all the pixels errors (overestimate in case of independent error)

From (Thomas and Prata, ACP 2011)

Plume altitude IASI vs CALIPSO



IASI - CALIPSO ~ 3h difference

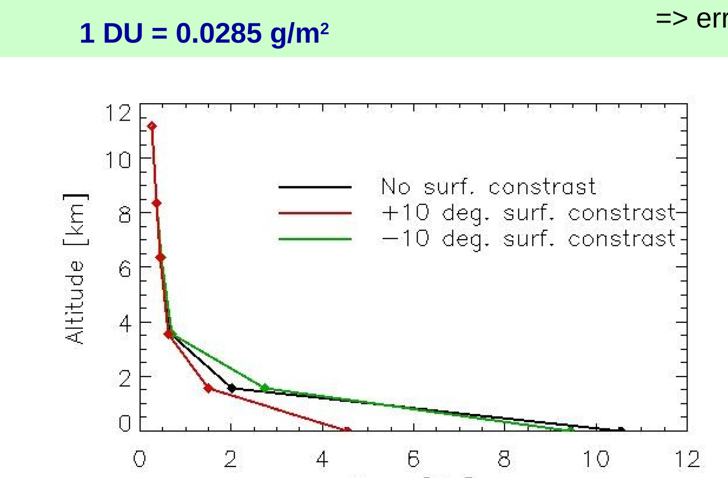
Minimum error estimate

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/m²

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

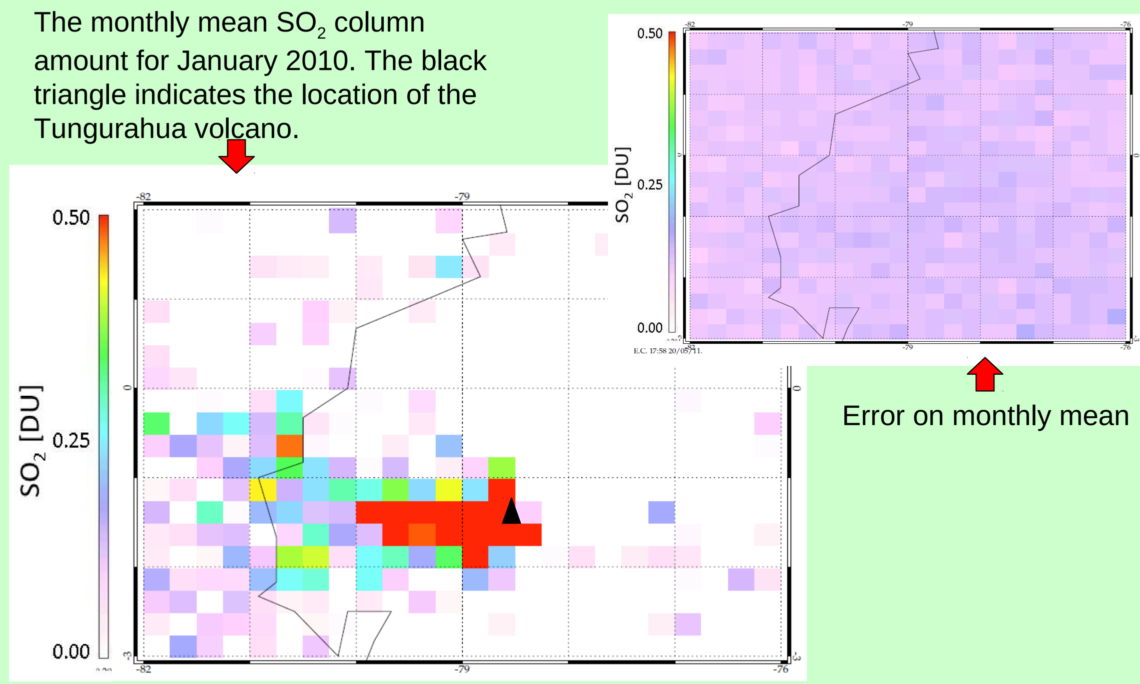


SO_2 monthly errors

[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}

Ecuador monthly mean - degassing

The monthly mean SO_2 column amount for January 2010. The black triangle indicates the location of the Tungurahua volcano.



Error on monthly mean

Summary and further work

New scheme for IASI developed to retrieve height and amount of SO_2.

Uses our new detection scheme (Walker et al. 2011) applied to pixels for the full retrieval.

Initial results seem to compare reasonably to other observations.

Though sometimes see much larger amounts then uv methods

Thick ash can affect the retrieval, recognizable from cost >2
Cloud at the same altitude or above the plume mask the So2 signal
Retrieving the ash and cloud (optical depth, altitude and effective radius) properties is possible and subject of parallel work at AOPP & RAL.

Next steps:

- SO2 ⇨ comparison with ground and others satellite measurements
- Altitude ⇨ compare with models and more comparison with CALIPSO, MIPAS.
- Combined retrieval IASI + G0ME-2