# The vertical distribution of volcanic $SO_2$ plumes measured by IASI

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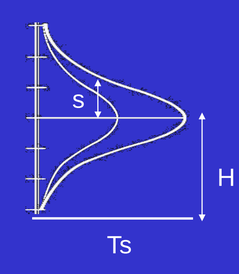
Sulphur dioxide ($SO_2$) is an important atmospheric constituent that plays a crucial role in many atmospheric processes. In the troposphere $SO_2$ injection leads to the acidification of rainfall while in the stratosphere it oxidises to form a stratospheric $H_2SO_4$ haze that can affect climate for several years. The Infrared Atmospheric Sounding Instrument (IASI) on the Metop satellite can be used to study volcanic emission of $SO_2$ using high-spectral resolution measurements from 1000 to 1200 cm-1 and from 1300 to 1410 cm-1 (the 7.3 and 8.7 um $SO_2$ bands). The scheme described in Carboni et al. (2012) has been applied to measure volcanic $SO_2$ amount and altitude for most explosive eruptions from 2008 to 2014, including large eruption such as Nabro and less intense events such as Etna lava fountains and the recent Bardabunga eruption. The work includes a comparison with independent measurements: (i) the $SO_2$ column amounts from the 2010 Eyjafjallajökull plumes have been compared with Brewer ground measurements over Europe; (ii) the $SO_2$ plumes heights have been compared with CALIPSO backscatter profile. The results of the comparisons show that IASI $SO_2$ measurements are not affected by underlying cloud and are consistent (within the retrieved errors) with the other measurements considered. The series of analysed eruptions, between 2008 and 2012, show that the biggest contributor of volcanic $SO_2$ was Nabro, followed by Kasatochi and Grímsvötn. Our observations also show a tendency of the volcanic $SO_2$ to be injected to the level of tropopause during many explosive eruptions. For the eruptions observed, this tendency was independent of the maximum amount of $SO_2$ erupted (e.g., 0.2 Tg for Dalafilla compared with 1.6 Tg for Nabro) and of the volcanic explosive index (between 3 and 5).

## 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). Uses the detection scheme (Walker et al. 2012) applied to pixels for the full retrieval (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 information 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 retrieval 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

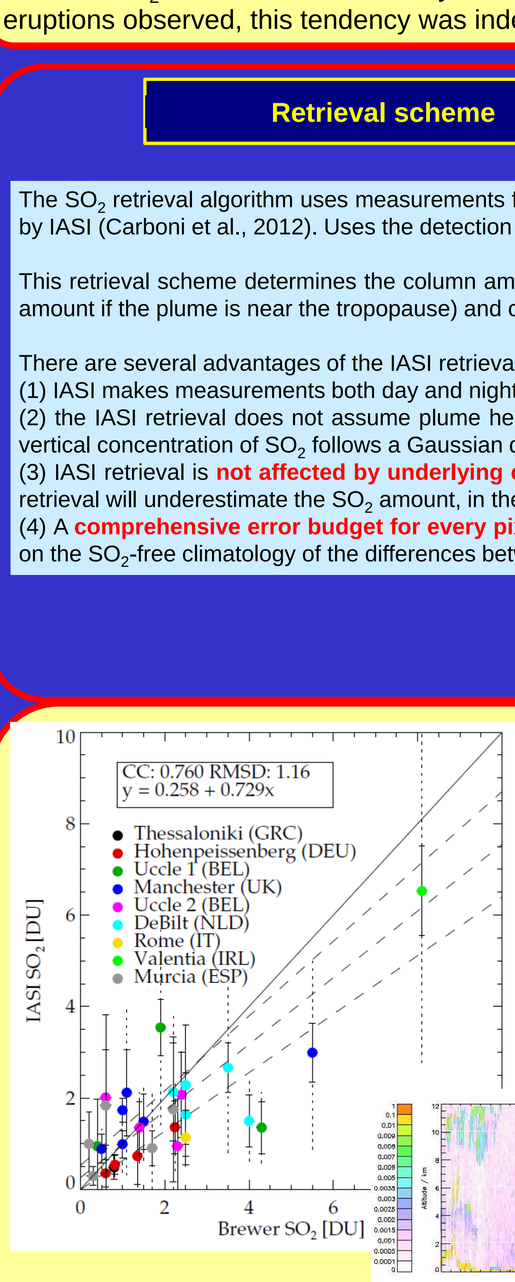
$$J = (\mathbf{y} - F(\mathbf{x}) - \mathbf{b})^T \mathbf{S}_e^{-1} (\mathbf{y} - F(\mathbf{x}) - \mathbf{b}) + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

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

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

Note that the measurement covariance, $\mathbf{S_e}$, 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.

## Comparison with Brewer ground data




Scatter plot of IASI $SO_2$ measurements, averaged within a distance of 200 km from the ground station, versus the daily $SO_2$ column amount, measured from Brewer spectrometers. Different colours correspond to a different ground station. Black error-bars are the IASI average errors; dotted error-bars are the standard deviation of the IASI data within the selected distance. Black lines represent the ideal line y=x; dotted lines are the best fits with error in the best fit

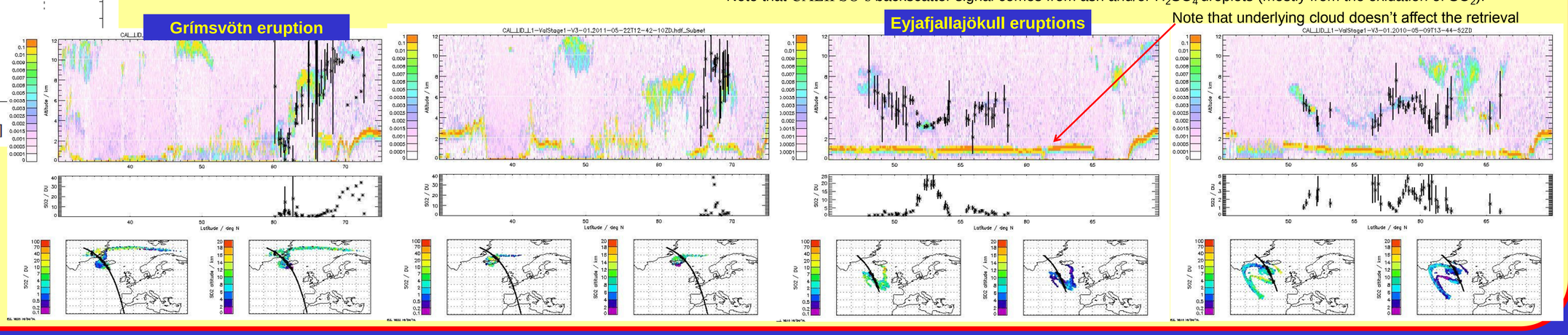
## Height comparison with CALIOP

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 $SO_2$).

Note that underlying cloud doesn't affect the retrieval

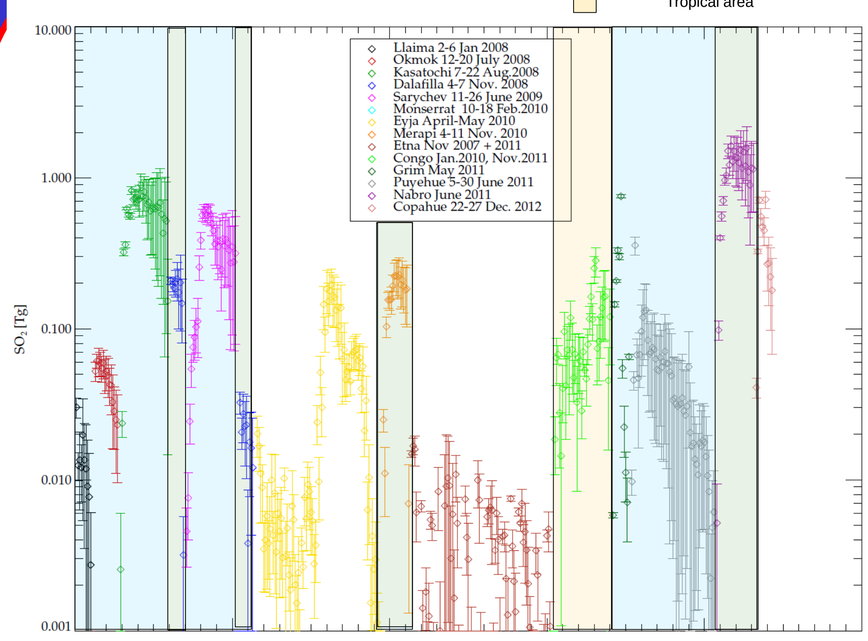
**Grímsvötn eruption** — **Eyjafjallajökull eruptions**




## Total mass

Tropopouse and up

Tropical area

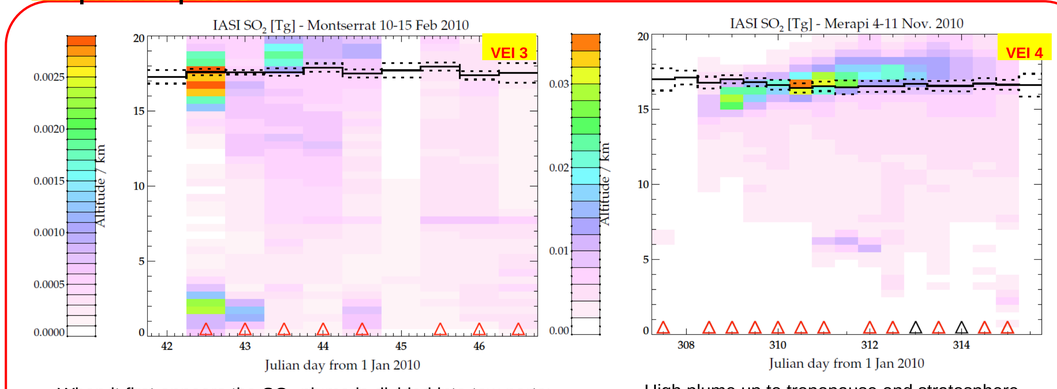



## Vertical distribution

In each plot the y axes are the vertical levels in km. The colour represents the total mass of $SO_2$ in Tg, dark-red represent values higher the the colour-bar. Every column of the plots comes from an IASI map (one every 12h). Red triangles in the bottom line indicate the presence of a fresh plume connected with the volcano, black triangles indicate the presence of an old plume overpassing the volcano. Note that the plots for different eruptions have different colour-scales and cover different time ranges. Black lines are the mean and standard deviation of the tropopause.
VEI (Volcanic Explosivity Index) is a qualitative scale of eruption size.

The VEI estimates quoted here are from Smithsonian Institution Global Volcanism Programme (http://www.volcano.si.edu).

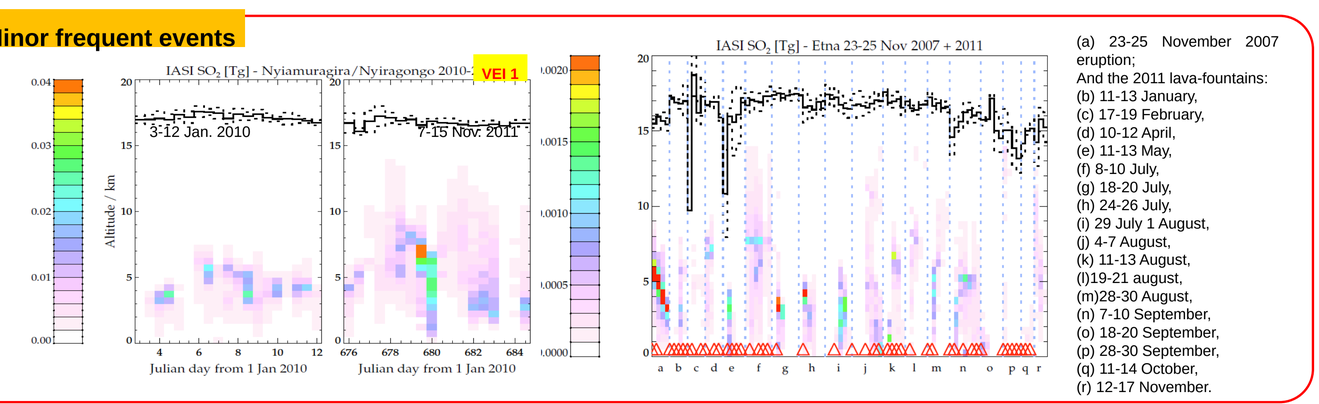
## Tropical eruptions




- When it first appears the $SO_2$ plume is divided into tow parts: a higher one around 16-19km (tropopause/stratosphere) and a lower one in troposphere.
- The lower plume disappears (non detectable) after one day, while the higher one spread east, south east.

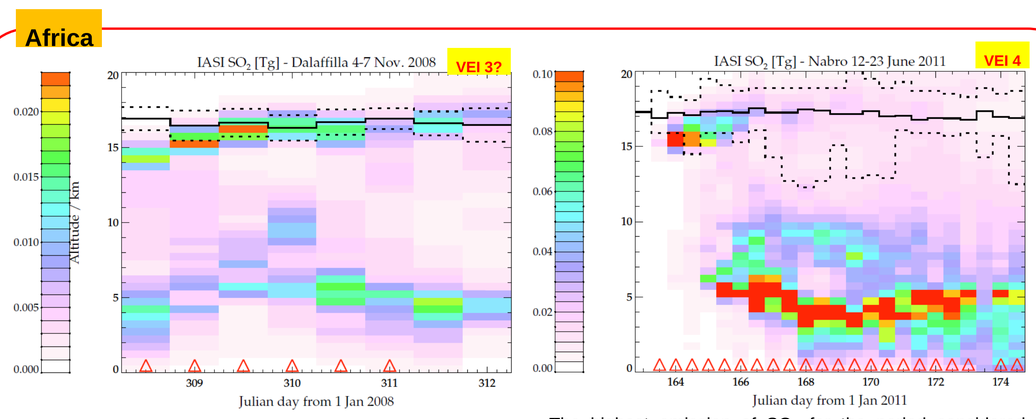
- High plume up to tropopause and stratosphere.
-(problems: old plume overpasses the volcano)

## Minor frequent events




(a) 23-25 November 2007 eruption;
And the 2011 lava-fountains:
(b) 11-13 January,
(c) 17-19 February,
(d) 10-12 April,
(e) 11-13 May,
(f) 8-10 July,
(g) 18-20 July,
(h) 24-26 July,
(i) 29 July 1 August,
(j) 4-7 August,
(k) 11-13 August,
(l)19-21 august,
(m)28-30 August,
(n) 7-10 September,
(o) 18-20 September,
(p) 28-30 September,
(q) 11-14 October,
(r) 12-17 November.

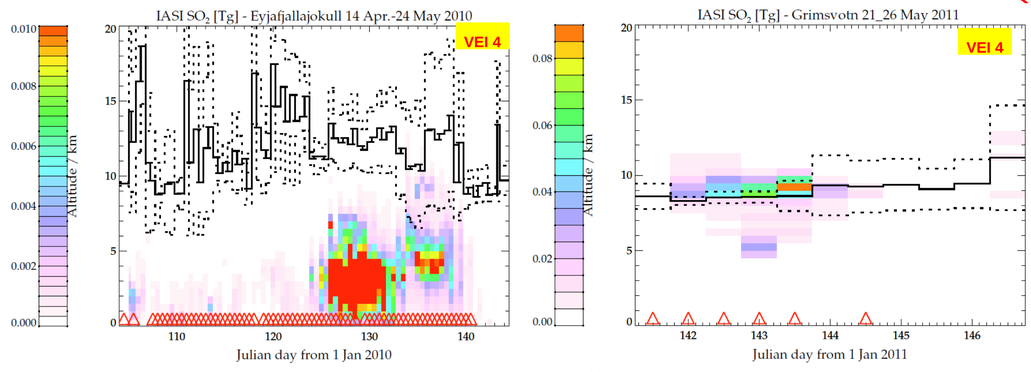
## Africa




- 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 high.

- 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 troposphere with 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.

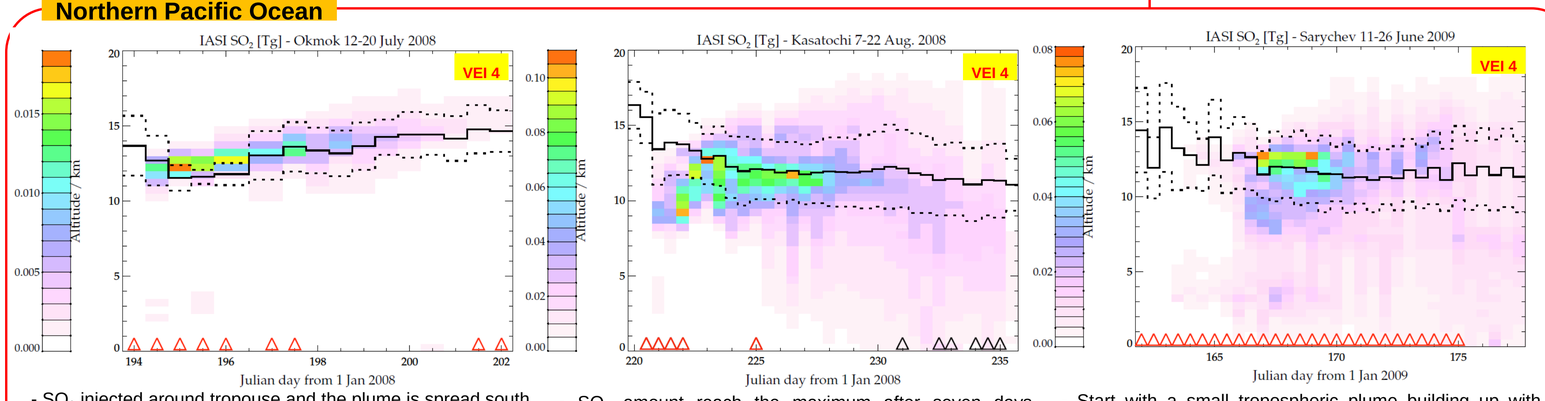
## Iceland




- $SO_2$ plume confined in troposphere.
- Up to 20 April the plume below 10km (mainly confined within first 5km); From 20 to 30 April plume < 5km; Increase on both amount and altitude from 5 May, with maximum altitude (around 10km) from 14 to17 May.

- Higher part of the plume moves west and spreads north arrive at tropopouse/stratosphere.
- Lower plume travelling toward Europe (together with ash), confined in troposphere.

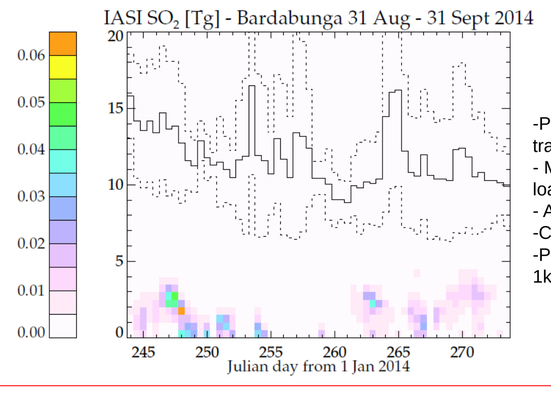
## Northern Pacific Ocean




- $SO_2$ injected around tropouse and the plume is spread south (pacific ocean) and east (north america)
- Presence of intermittent smaller and lower plume connected with the volcano.
- Main plume altitude increase with time following the tropopouse altitude.

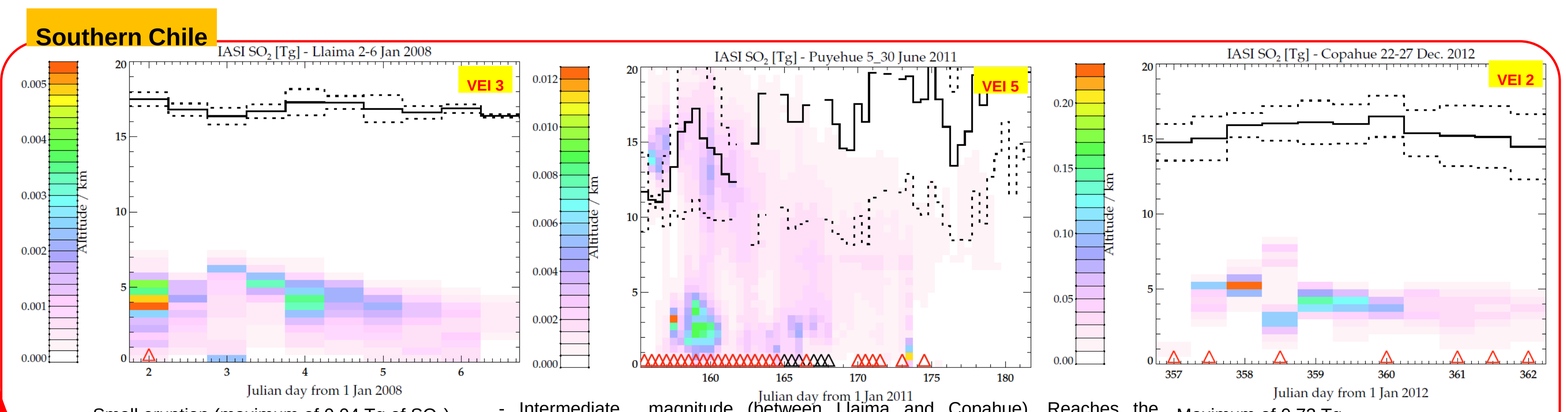
- $SO_2$ amount reach the maximum after seven days indicating continuous injection from volcano.
- Within ten days $SO_2$ plume affect all latitude between 30-90°N.
- Arrive to tropopouse and stratosphere.

- Start with a small tropospheric plume building up with increasing $SO_2$ load with a maximum on 16th June (0.6 Tg)
- Arrive to tropopouse and stratosphere.




-Plume injected into lower troposphere, transported over then 2500km away,
- Maiximum total mass atmospheric loading (in September 2014) 0.17 Tg
- Affected air quality over Europe
-Centre of mass altitude around 3 km,
-Possibility of undetected plume below 1km

## Southern Chile




- Small eruption (maximum of 0.04 Tg of $SO_2$)
- Plume connected to the volcano only the first day.
- Confined in troposphere.

- Intermediate magnitude (between Llaima and Copahue), Reaches the stratosphere and we can follow the plume 3 times around the sothern hemisphere in ~ 30 days.
- First part of the eruption is higher in $SO_2$ amount and altitude.
- Intermittent low plume connect with the volcano for all the period considered.

- Maximum of 0.72 Tg.
- Plume connected with volcano every days
- Confined in troposphere.

## Summary

IASI retrieved values are consistent with the satellite (CALIPSO) and ground measurements (Brewer).
The IASI scheme has been used twice a day to follow the vertical distribution of $SO_2$ as a function of time, for different eruption types (e.g. VEI ranging between 1 and 5) and different latitudes. There is a tendency for volcanic $SO_2$ plumes to reach a point of buoyancy near the tropopause. All of the eruptions in the tropics (except Nyamuragira), reach the tropopouse. In the mid latitudes, the eruptions of Eyjafjallaj¨okull, Lima, Copahue and Etna remained confined in the troposphere.

**ACKNOWLEDGMENTS**

A special thanks to EODG group for support and discussions.

This work has been supported by COMET (NERC), Vanaheim (NERC) and SMASH (ESA) projects.

**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.